

Collider Searches for Physics Beyond the Standard Model

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For the CDF and D0 collaborations

Physics in Collision

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High energy collider searches

- Tevatron and HERA are highest energy colliders currently running (HERA shuts down tomorrow)
- On the eve of the LHC startup
 - Tevatron/HERA are making interesting contributions
 - Unique signatures, lots of new results, possible hints?
 - Low-mass SUSY, Higgs could be easier to find at Tevatron compared to LHC
- We have the data in hand now...
 - HERA producing results with final dataset
 - Tevatron 3/fb -- Will run for at least two more years!
- This talk:
 - Focus on Tevatron searches
 - HERA searches covered in other talks
 - See Iris Abt's talk on Wednesday
 - See Thi Nguyet Trinh's talk today on H1 searches
 - I'll show a few examples

Accelerators: Tevatron and HERA

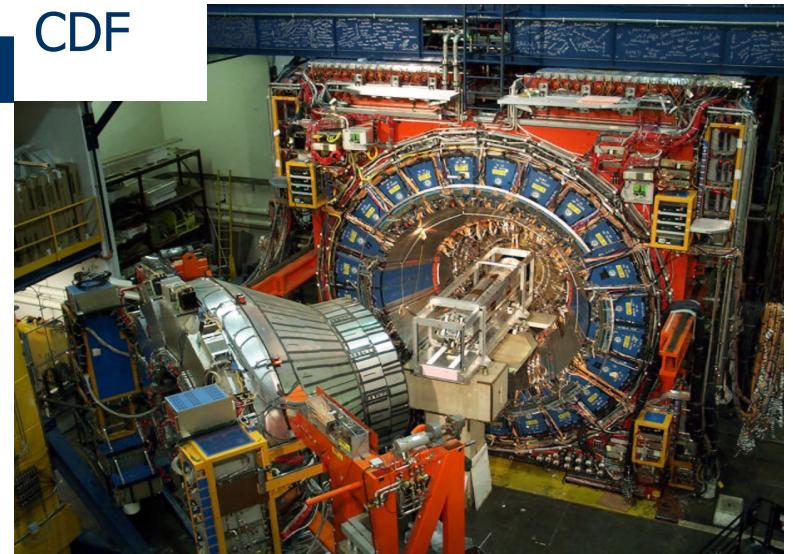
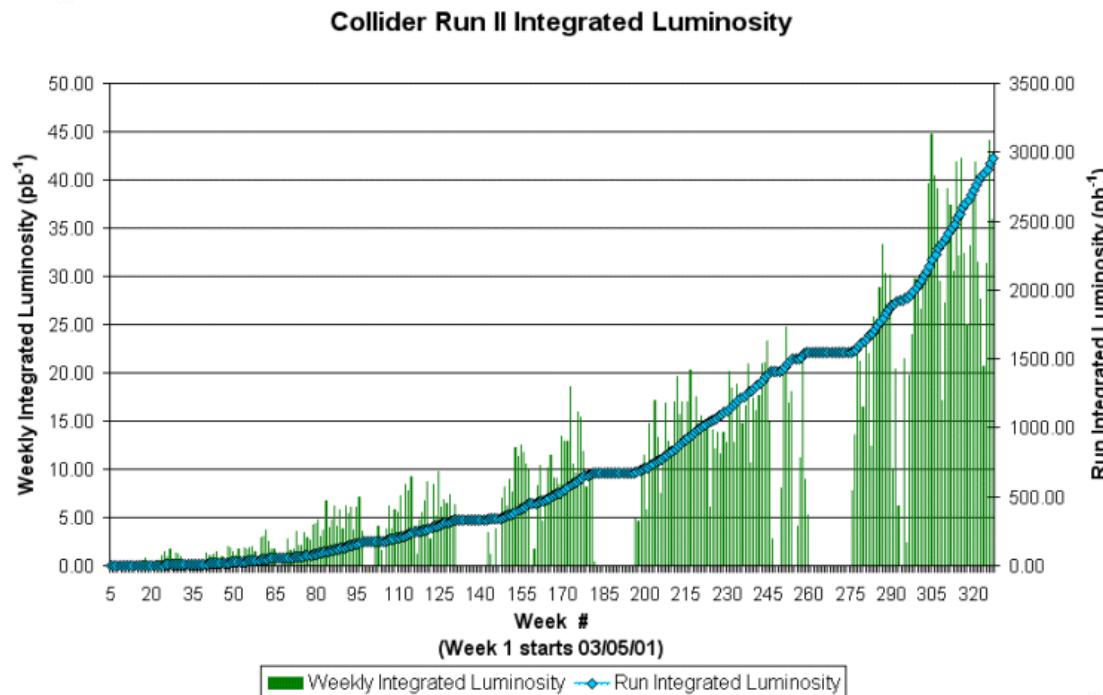


HERA: $e^{+/-}$ p
27.5 460-920GeV
Ecm=300-320



Tevatron Run 2

CDF



DØ

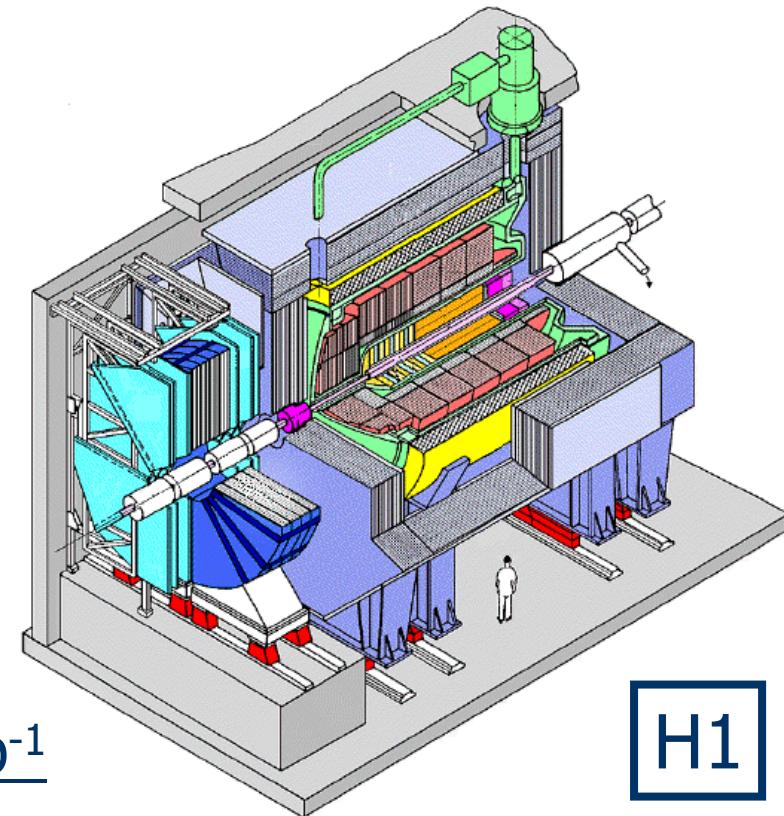
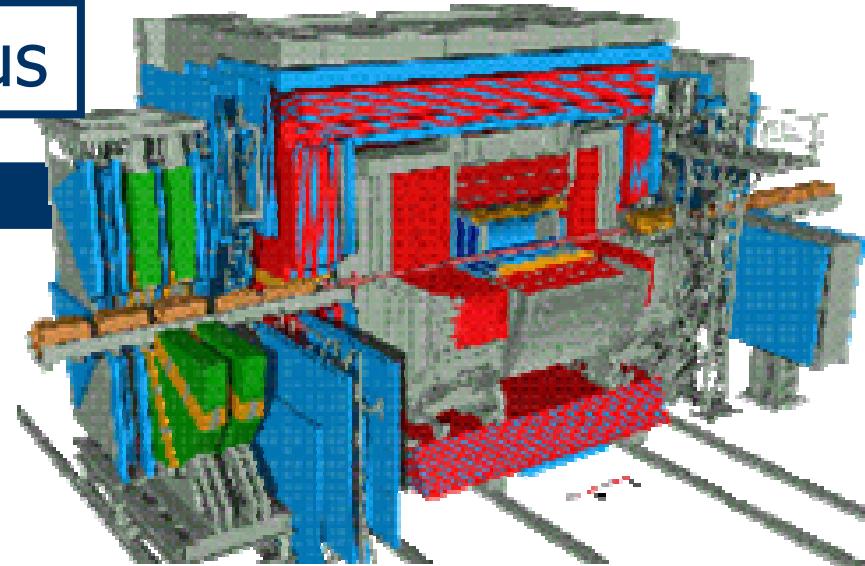
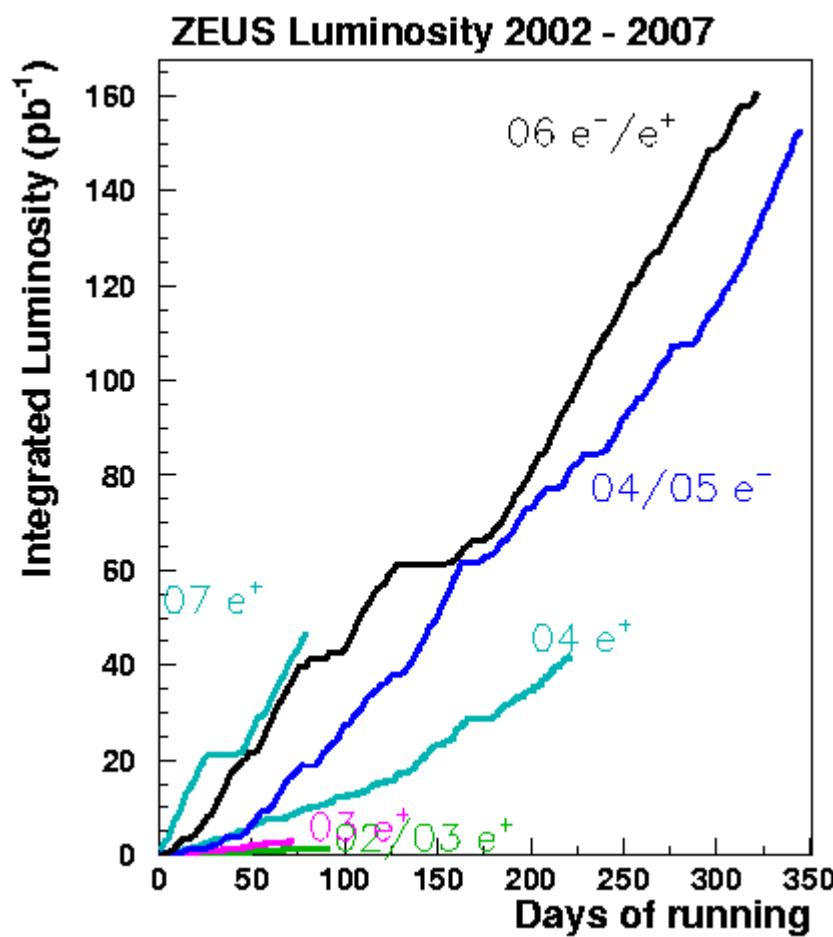


~3 fb^{-1} recorded!
4-8 fb^{-1} by 2009

Today's results are
mostly with 1+ fb^{-1}
2 fb^{-1} this summer

HERA

Zeus



H1 + Zeus together collected 1 fb $^{-1}$

H1

How do we look for new physics?

- We're looking for something new – what can we see?
 - Relatively high cross sections ($O(100\text{fb}-1\text{pb})$) can be seen if Standard Model (SM) background can be overcome
 - High signal/background (S/B) can use hypothesized kinematic differences to separate S from b
 - Examples : resonance in mass spectrum, excess in high tail of transverse momentum, excess of unusual events
 - Less dependent on our guess of signal, but rely on modeling of SM processes
 - Tricky – fluctuation or signal?
 - For low S/B signals, need more sophisticated analysis techniques
 - Neural Nets, Matrix Elements
 - Rely on good knowledge of signal and background
 - Perfect for SM signals such as Higgs and single top!

What do we look for?

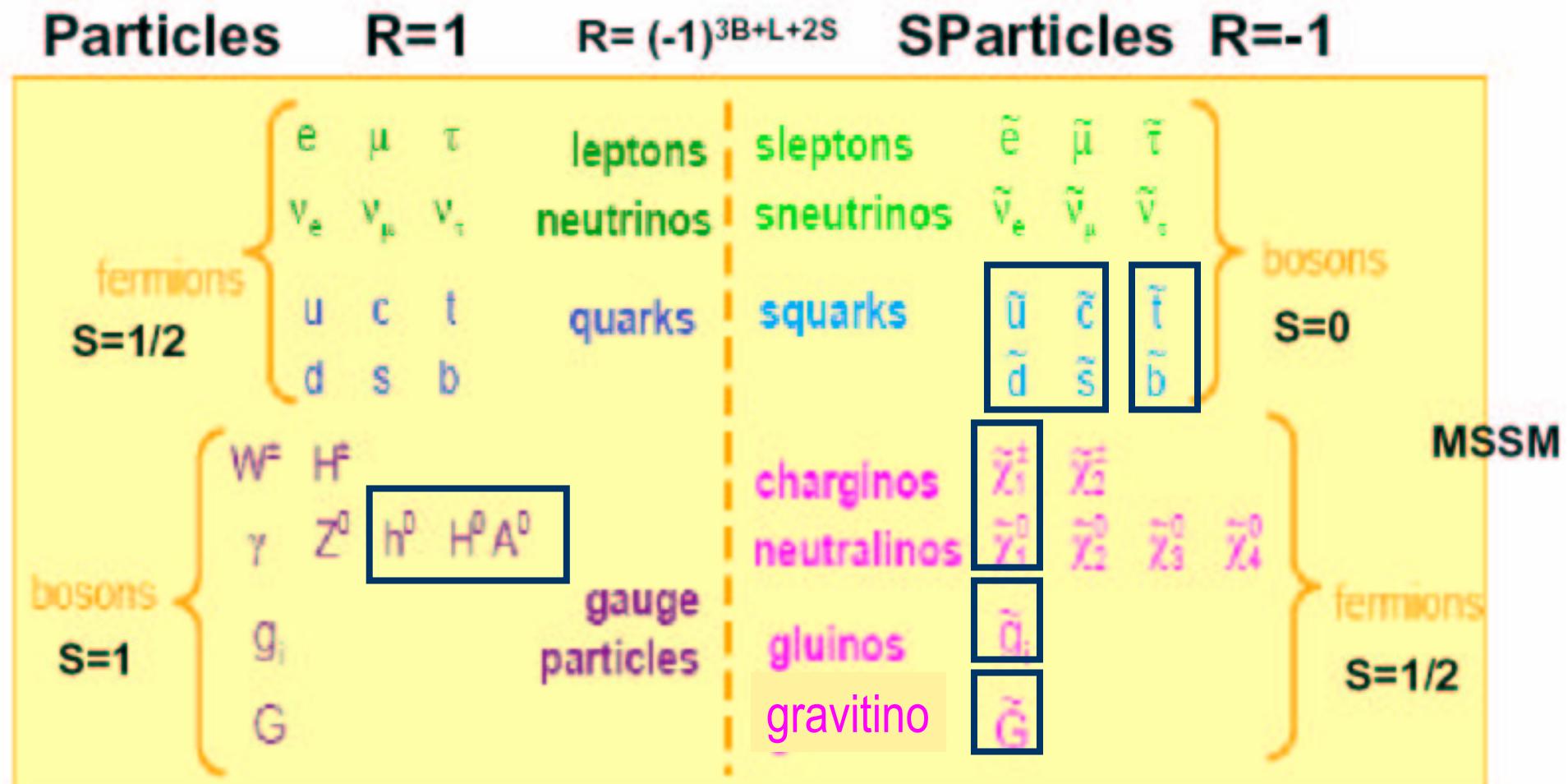
Combine theoretical motivation, experimental constraints, and attempt to be inclusive – don't want to miss the unexpected!

- Extensive programs to search for Supersymmetry
 - “standard” MSSM-inspired (or mSUGRA) signatures
 - Combinations of leptons, jets, heavy-flavor tags, missing energy
 - GMSB, AMSB models
 - Long-lived particles give a variety of unique signatures
 - Indirect searches – $B_s \rightarrow \mu\mu$ (not discussed today)
 - Tevatron-- R-Parity Conserving, HERA -- RP Violating
- Searches for Extra Dimensions --Resonances, excesses in MET+jets
- Leptoquarks
- contact interactions, excited leptons
- 4th generation particles
- Signature-based, (quasi)model-independent searches

Supersymmetry (SUSY)

- SUSY is theoretically very popular, but no evidence in spite of 20+ years of searching
- SUSY predicts a new particle for every Standard Model (SM) particle (fermions become SUSY bosons, bosons become SUSY fermions)
- Why SUSY?
 - Solves theoretical problems in SM
 - Many models which could explain Dark Matter (DM) predict signatures accessible at Tevatron
 - Coincidentally, low-mass particles which could be seen at the Tevatron make the best DM candidates
 - Supersymmetry (SUSY) provides a good DM candidate in the lightest neutralino – neutral, colorless, does not decay
 - Tevatron searches for evidence of supersymmetric particles which decay to the lightest neutralino
 - Variety of signatures, models, direct and indirect searches

SUSY Particles



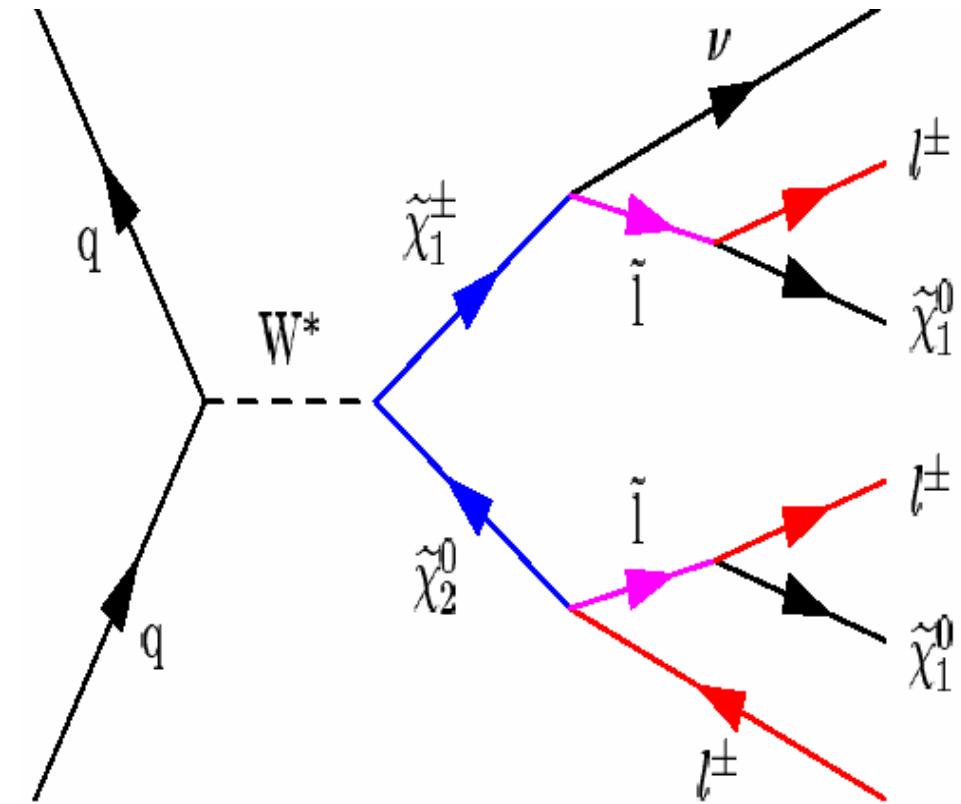
MSSM has 124 parameters:

M_1, M_2, M_3 , Gaugino masses, Sfermion masses
 $\tan\beta, \mu, m_A$ Higgs(ino) mass/mixing
 A_u, A_d, A_s (+45 RPV)

■ SUSY is a broken symmetry

Search for Chargino-Neutralino Production

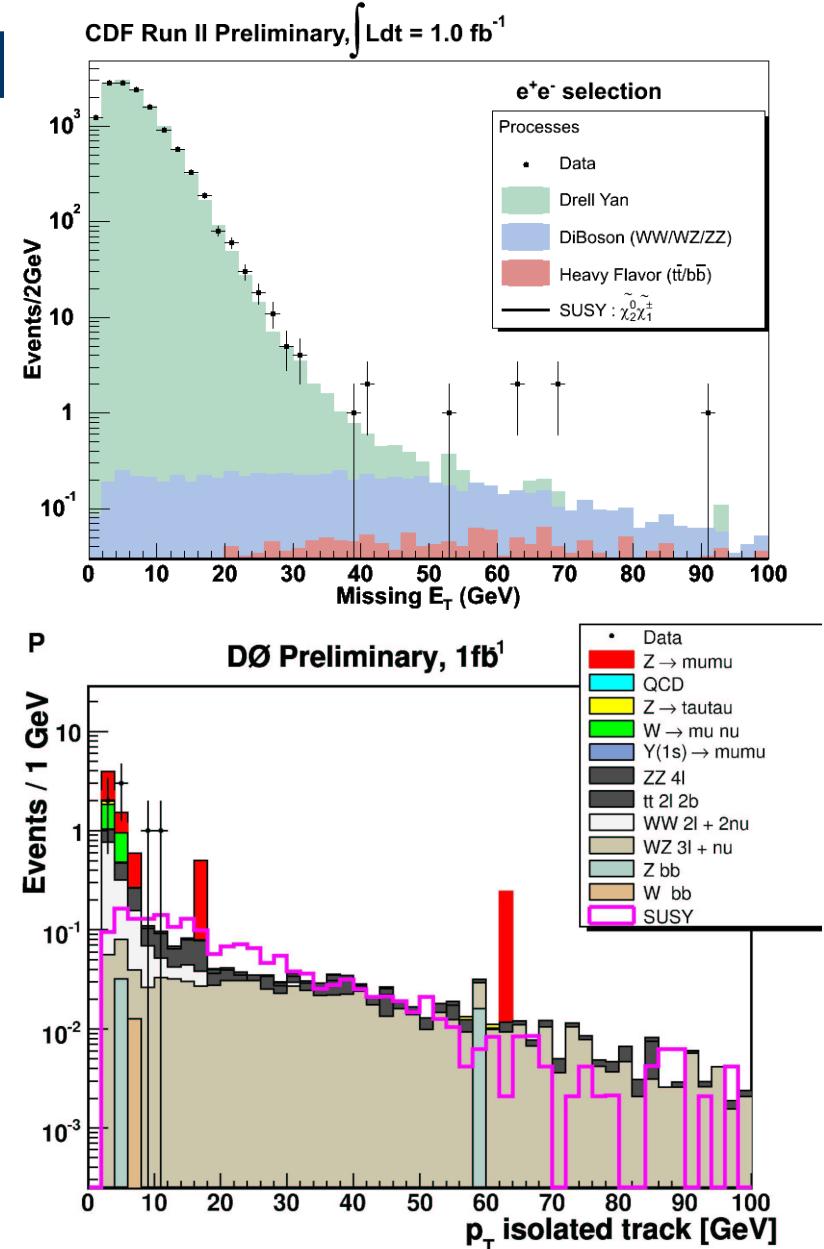
- Trileptons from chargino-neutralino: flagship analysis for discovery of SUSY at the Tevatron



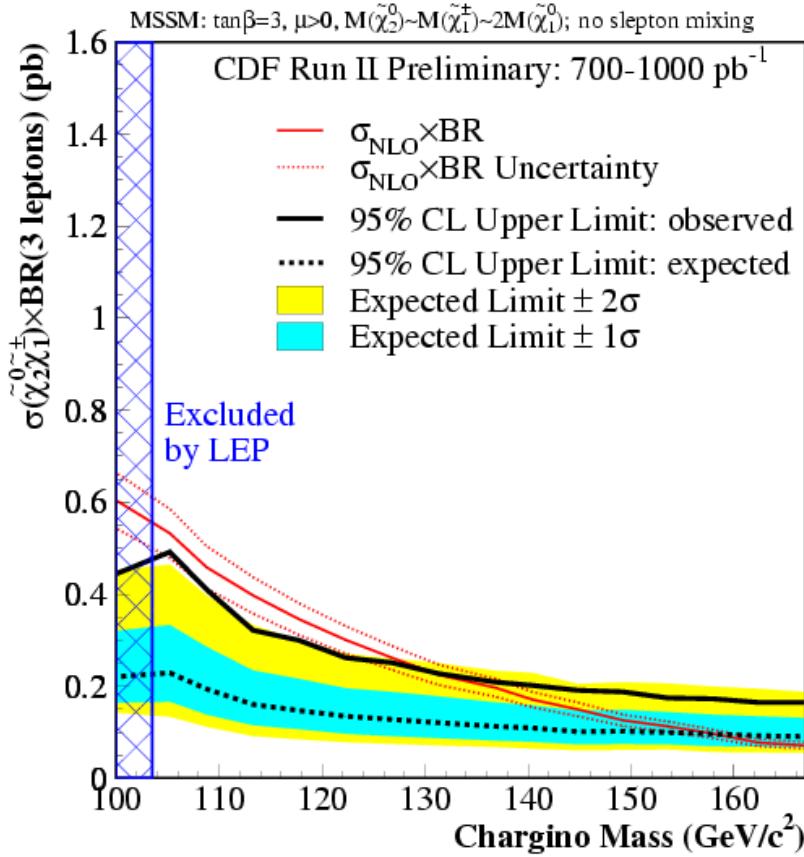
Clear signature – 3 isolated leptons, missing ET

CDF and D0 Trilepton Searches

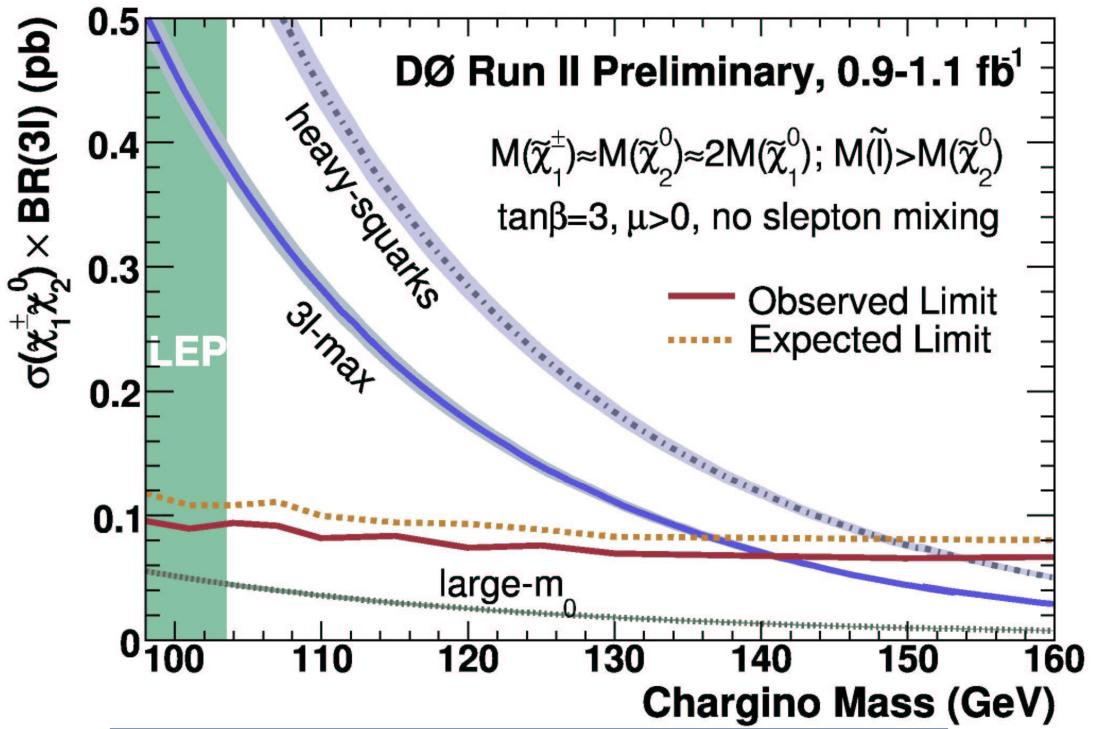
- CDF and D0 have a suite of searches for trileptons – combinations of electrons, muons, tracks (for 3rd lepton)
 - Taus are more difficult to detect, larger background from jets misidentified as taus
 - Gain acceptance by allowing track for 3rd lepton
 - Searches for more energetic leptons are simpler– fewer problematic backgrounds
 - Low energy searches needed to cover SUSY parameter space
 - Gain acceptance by searching for only two leptons – with the same sign
- Use control regions for bkg check



Constraining SUSY models



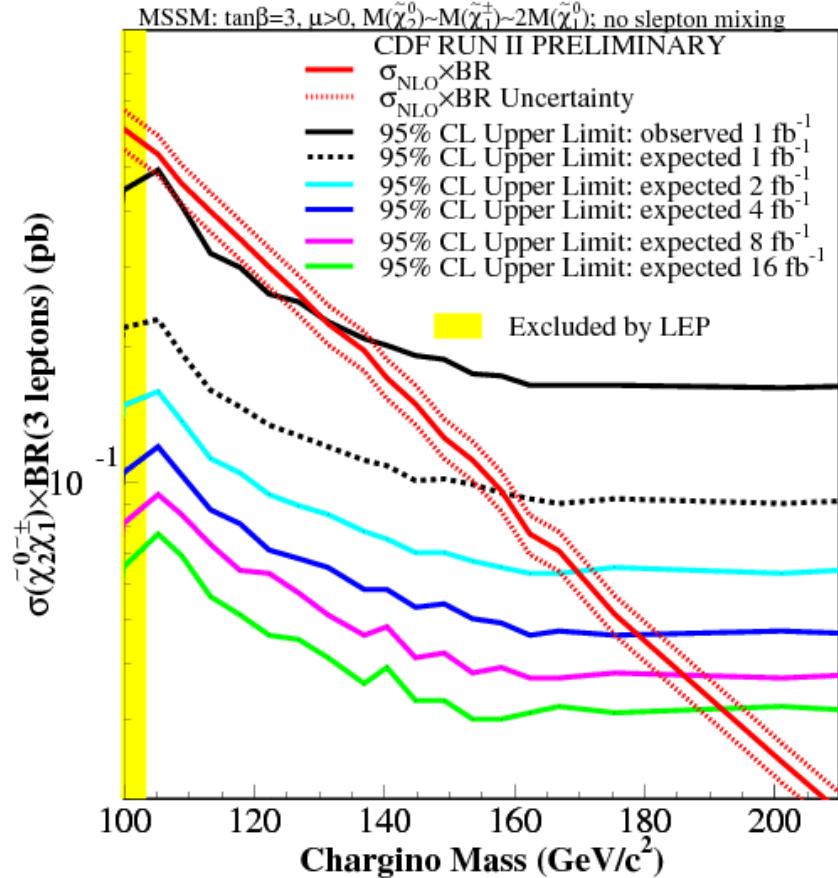
- No excess observed -- combine all trilepton channels to set a limit on the chargino mass in a specific model



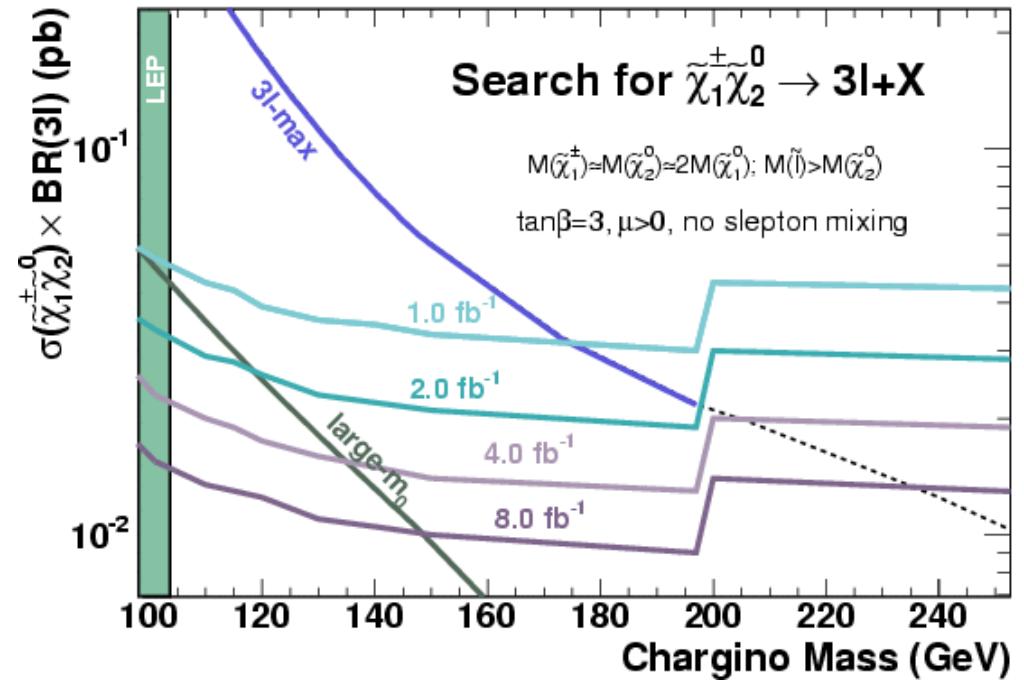
- CDF and D0 – similar but not identical models

- CDF – fix m_0
- D0 – adjust m_0 so that $m(\text{slepton}) > m(\text{chi}2)$

Trileptons – what could we see?



- CDF projected sensitivity based on $1/\text{fb}$ analyses expected sensitivity

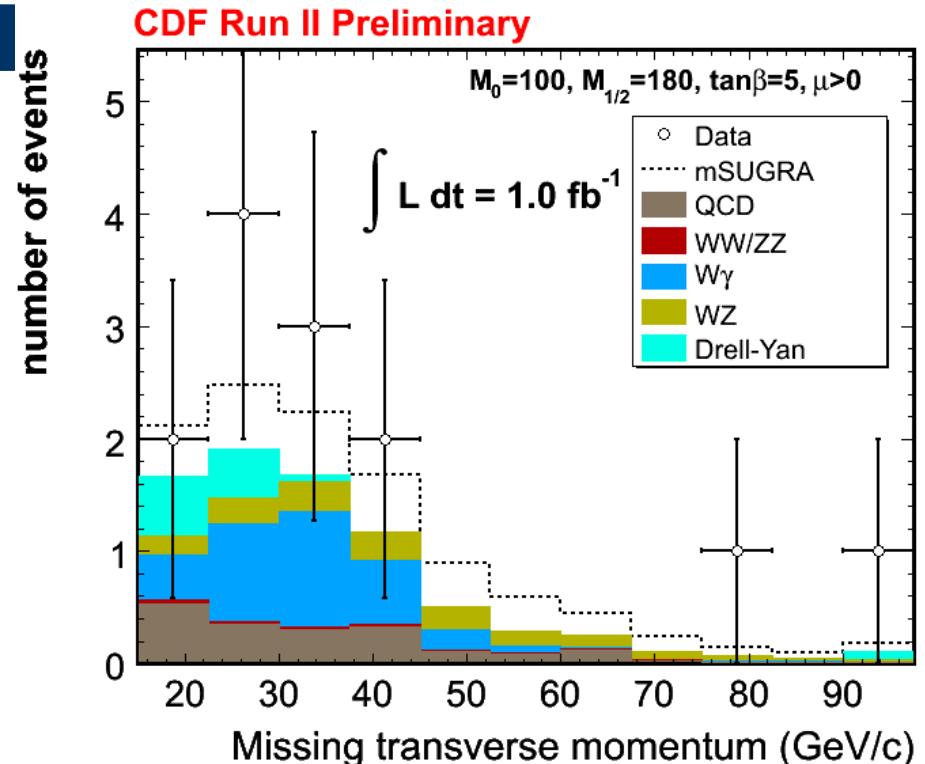
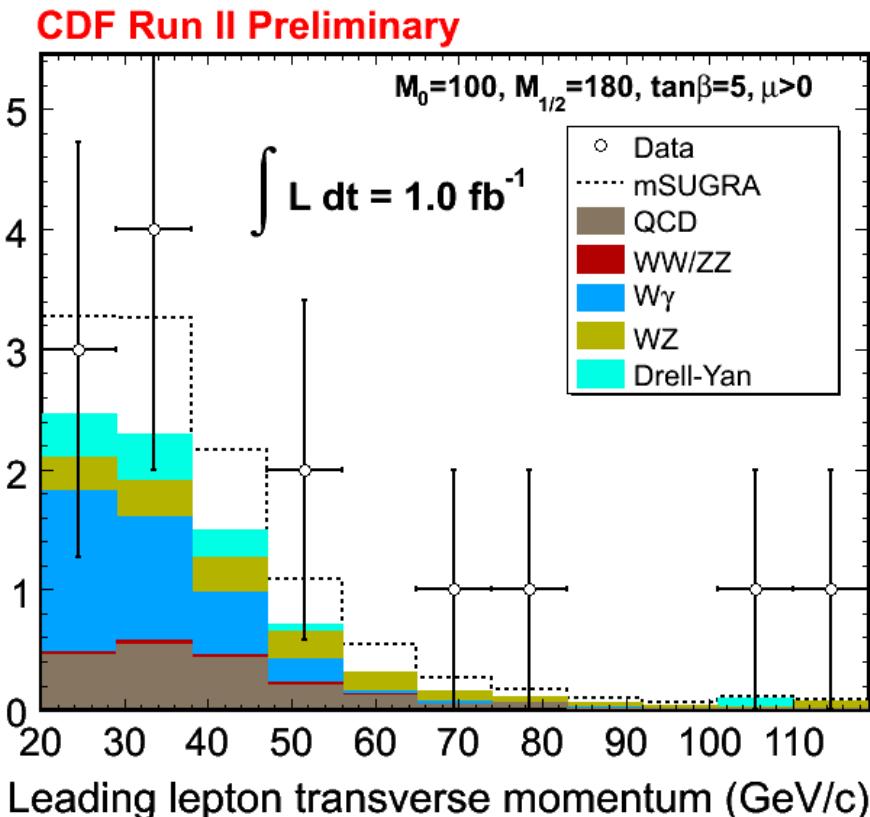


- D0 projections

- Assume improvements to analysis
- new decay modes at high mass spoil trilepton signature

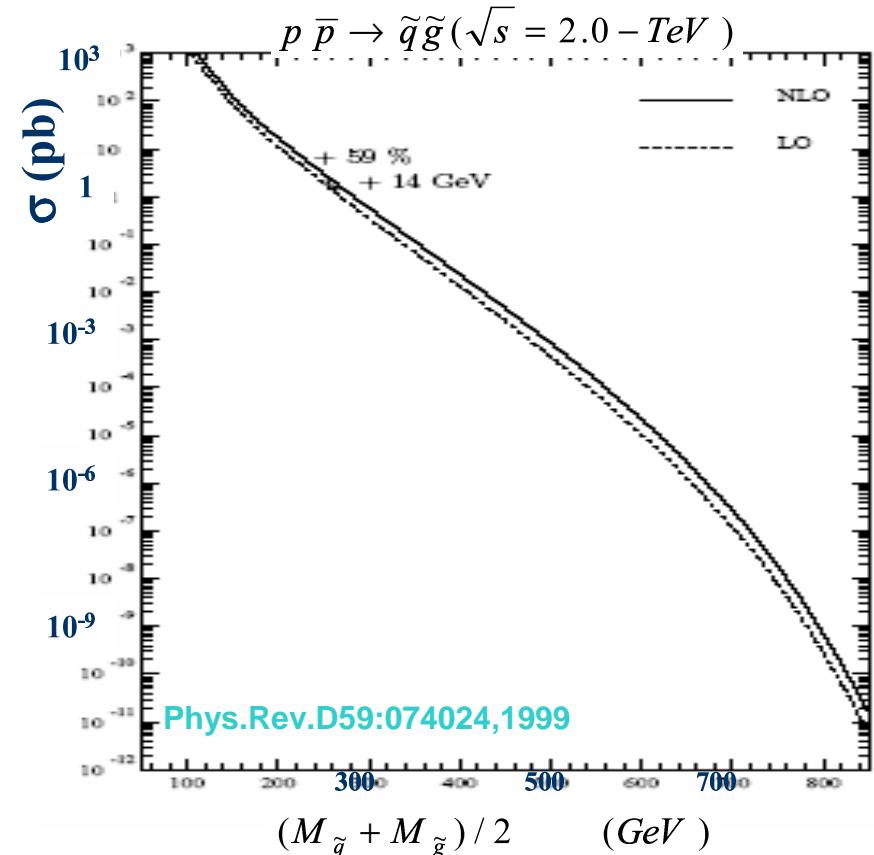
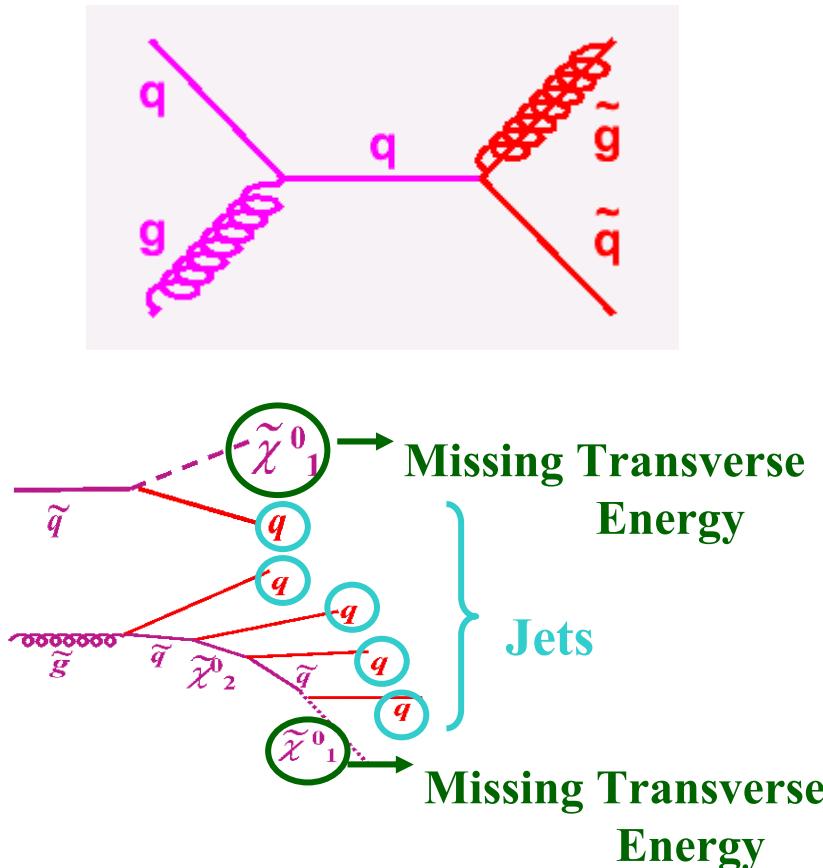
Like-Sign dileptons

- Signature-based search -- low Standard Model background
- Currently: chargino-neutralino production



Basic selection: expect 34+/-4, see 44
Tight selection: expect 8 +/- 1, see 13
Small excess at high pt – waiting to see in new data

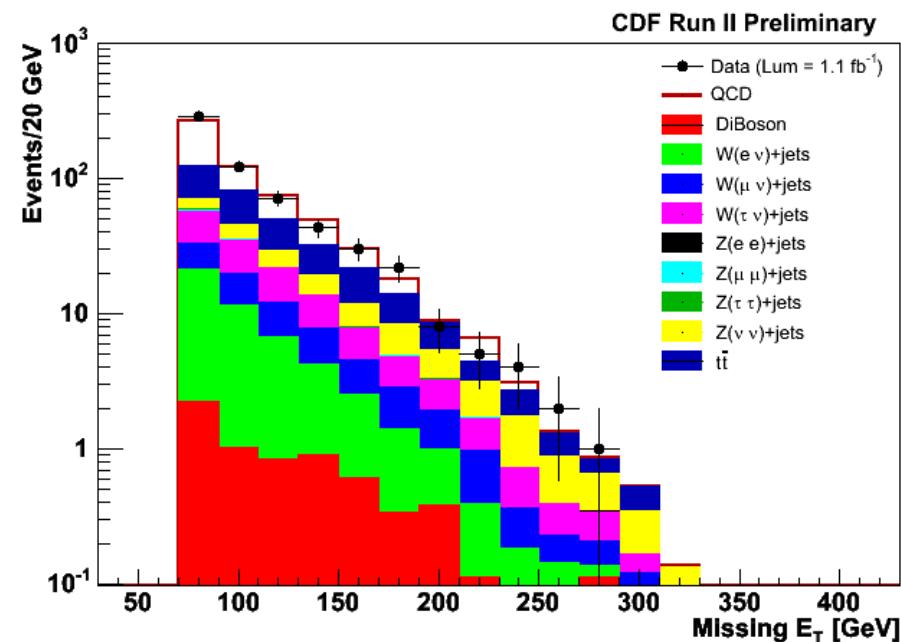
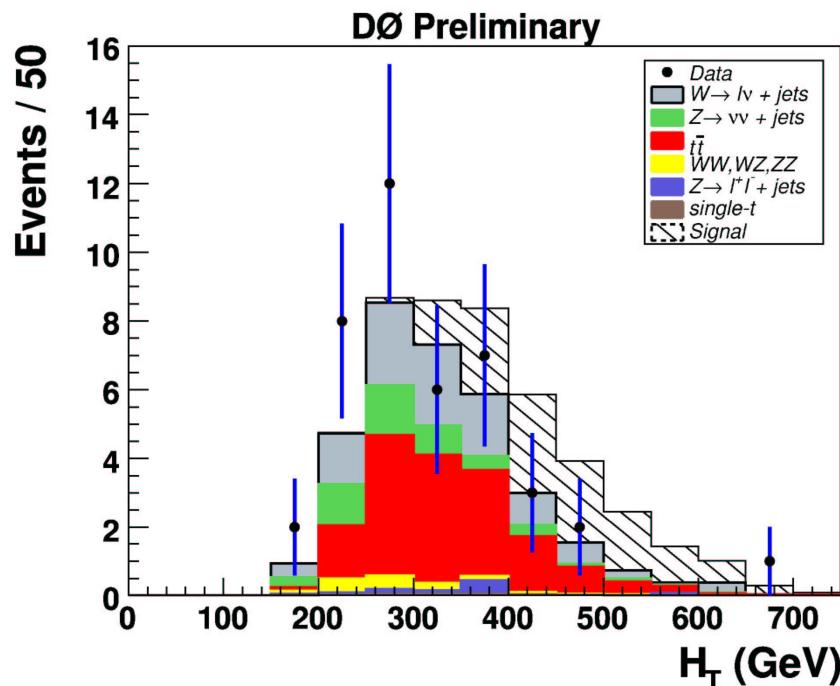
Tevatron Searches for Squark/Gluino Production



Strong interaction \rightarrow large production cross section
-- could give first evidence of SUSY!

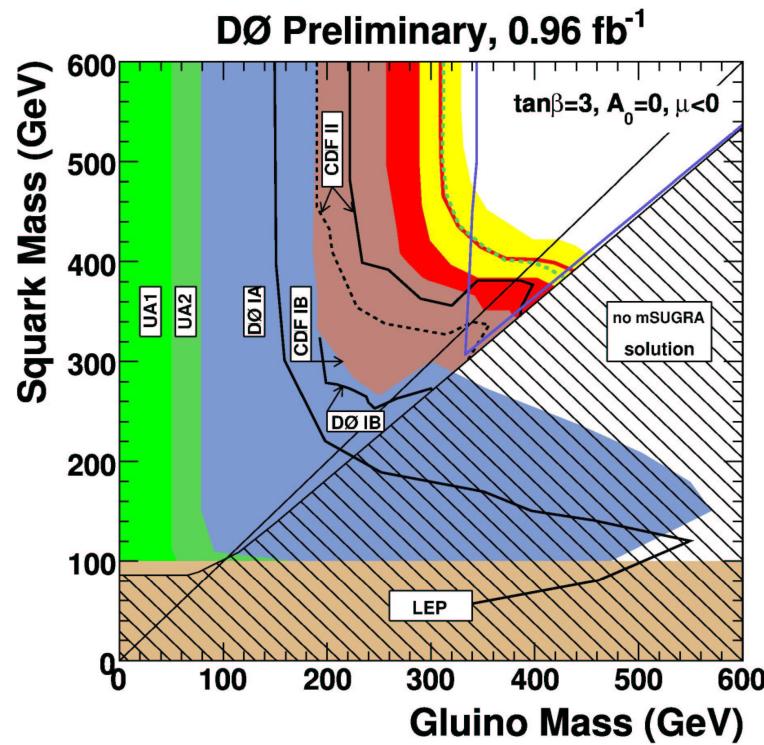
Search for Squark/Gluino Production

- Generic squark/gluino production → energetic jets ($N=2,3,4$ depending on decay), large missing ET
 - One of most powerful, general SUSY searches at the Tevatron
 - Also one of the most difficult – large QCD background



HT = scalar sum of ET of jets

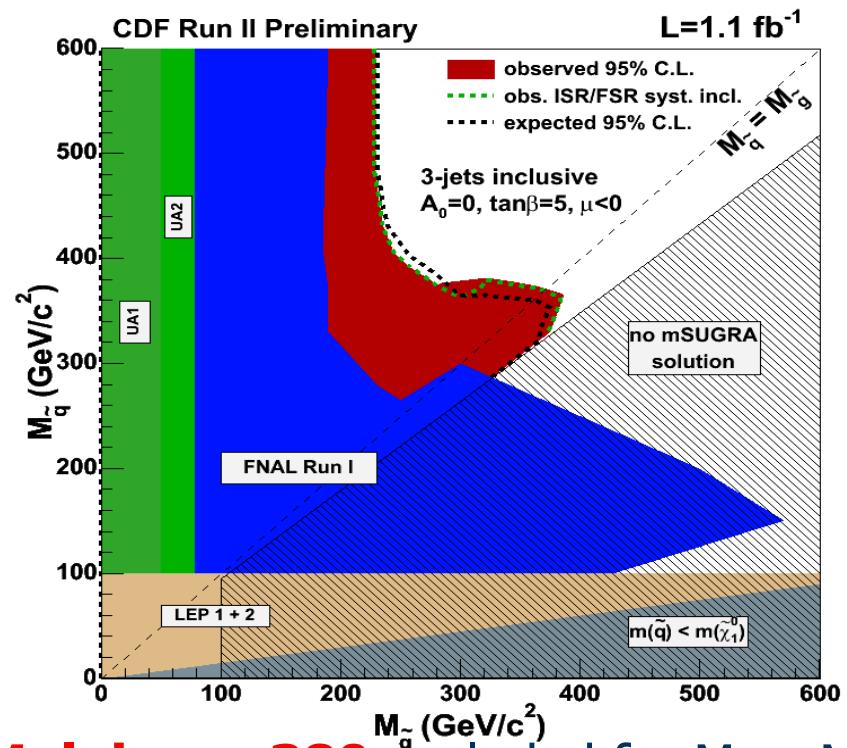
Limits on Squark/Gluino Production



Mgluino < 402 excluded for $Mg \sim Mq$

Mgluino < 309 excluded – any Mq

Use nominal values (not reduced for systematic errors) for signal cross sections (limits shown are $\sim 20 \text{ GeV}/c^2$ higher)

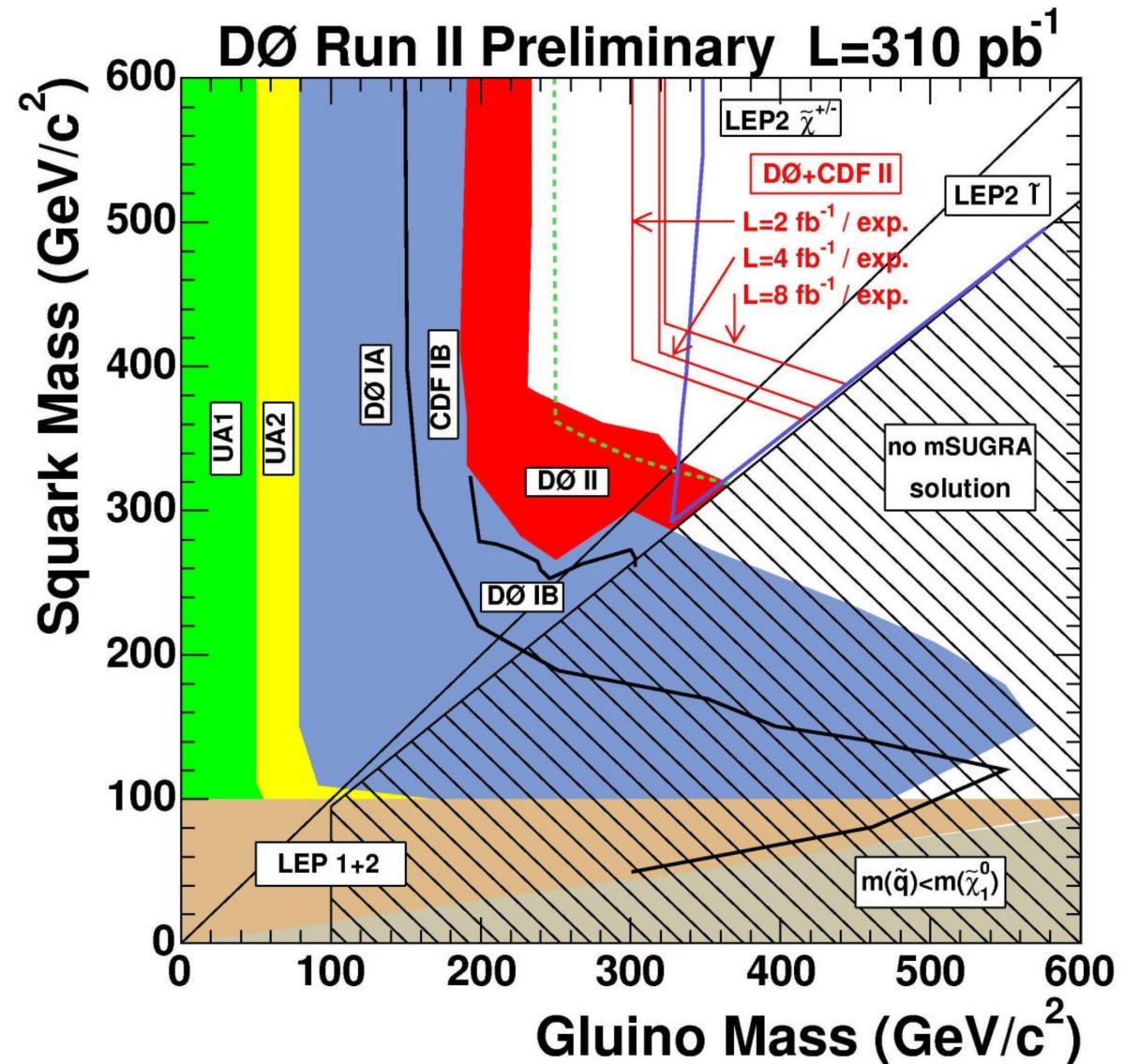


Mgluino < 380 excluded for $Mg \sim Mq$

Mgluino < 230 excluded -- any Mq

Projections for Squark/Gluino Searches

- D0 estimates sensitivity
- Assumptions:
 - Improved jet energy scale
 - Background scaled with luminosity (no high mass optimization)
 - Extrapolate efficiencies from lower mass

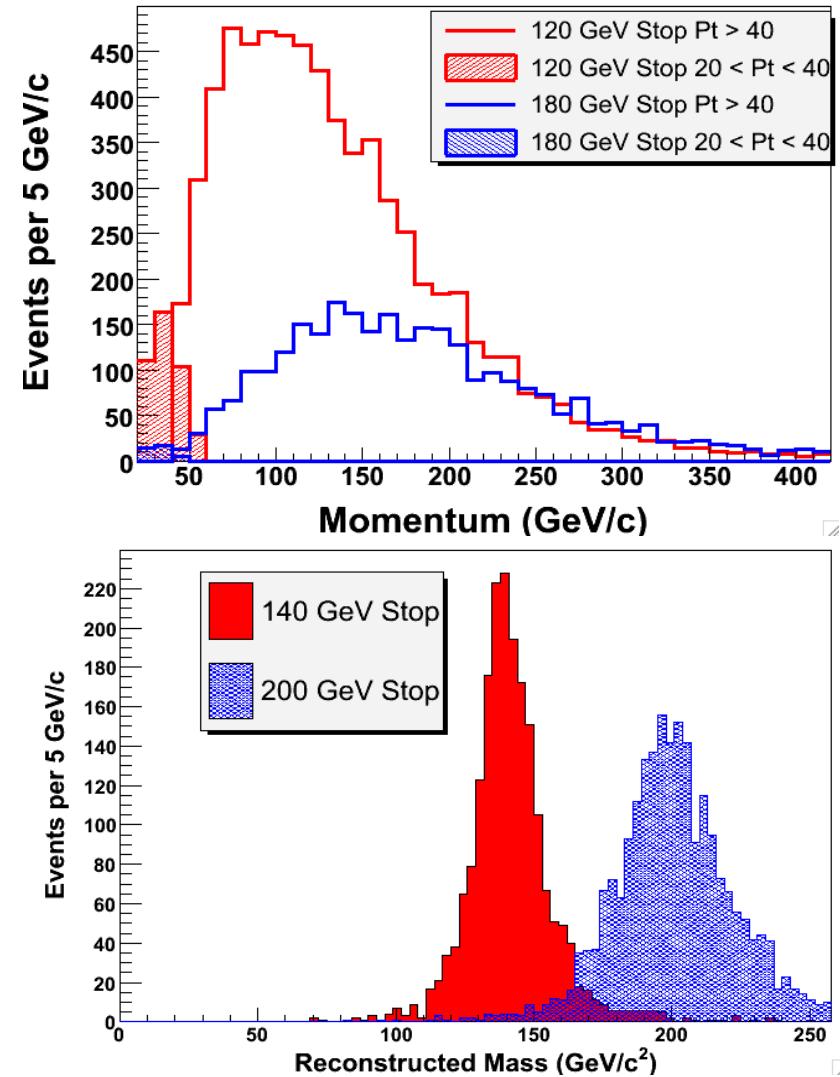


Long-lived Exotic particles

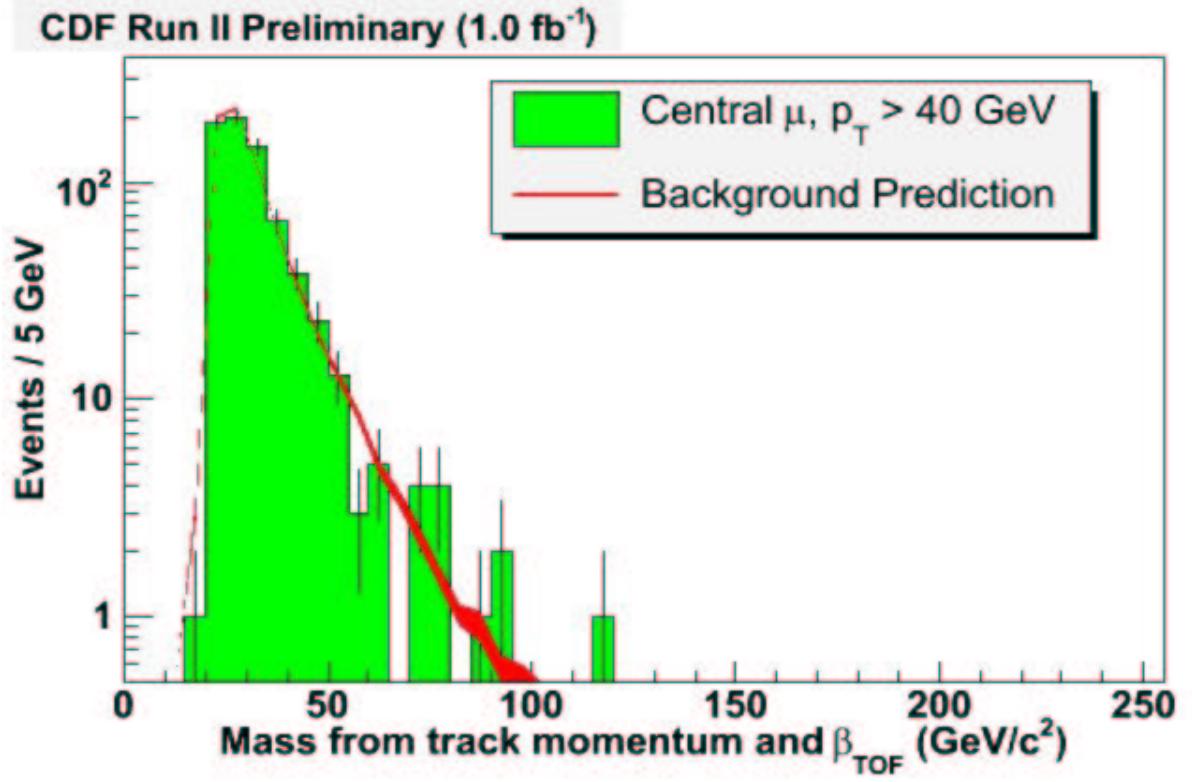
- Several models predict long-lived particles: charged or neutral, decaying inside or outside detector
 - Charged
 - looks like slow muon ← CHAMPS analysis
 - Neutral
 - decay inside detector
 - delayed photons ← CDF analysis
 - delayed jets ← D0 analysis

CDF Champs Search

- CHAMPS leave a unique signature
 - Look like slow, heavy muons – penetrating, long Time-of-Flight measured in detector, large ionization dE/dX
 - Large mass (from velocity and momentum measurements)
- Use control datasets to validate mass measurement



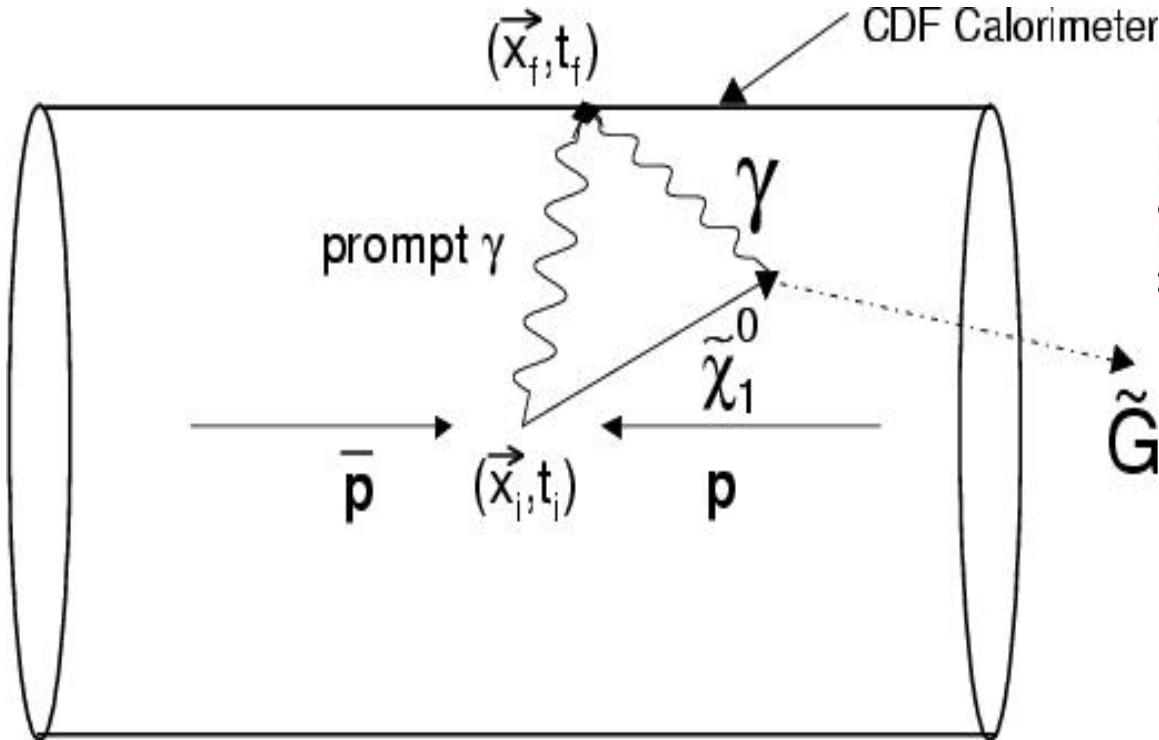
CHAMPS results



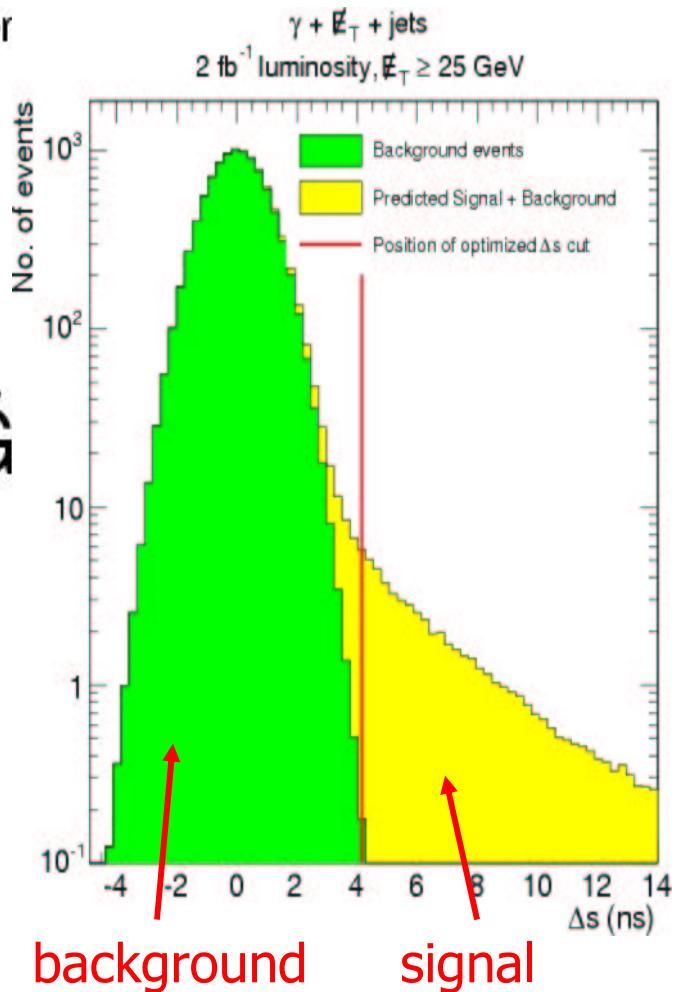
- Signal region – no candidates with $M > 120$. consistent with expected background
- Exclude stable stop with $M < 250 \text{ GeV}/c^2$ at 95%CL

CDF Delayed Photon Analysis

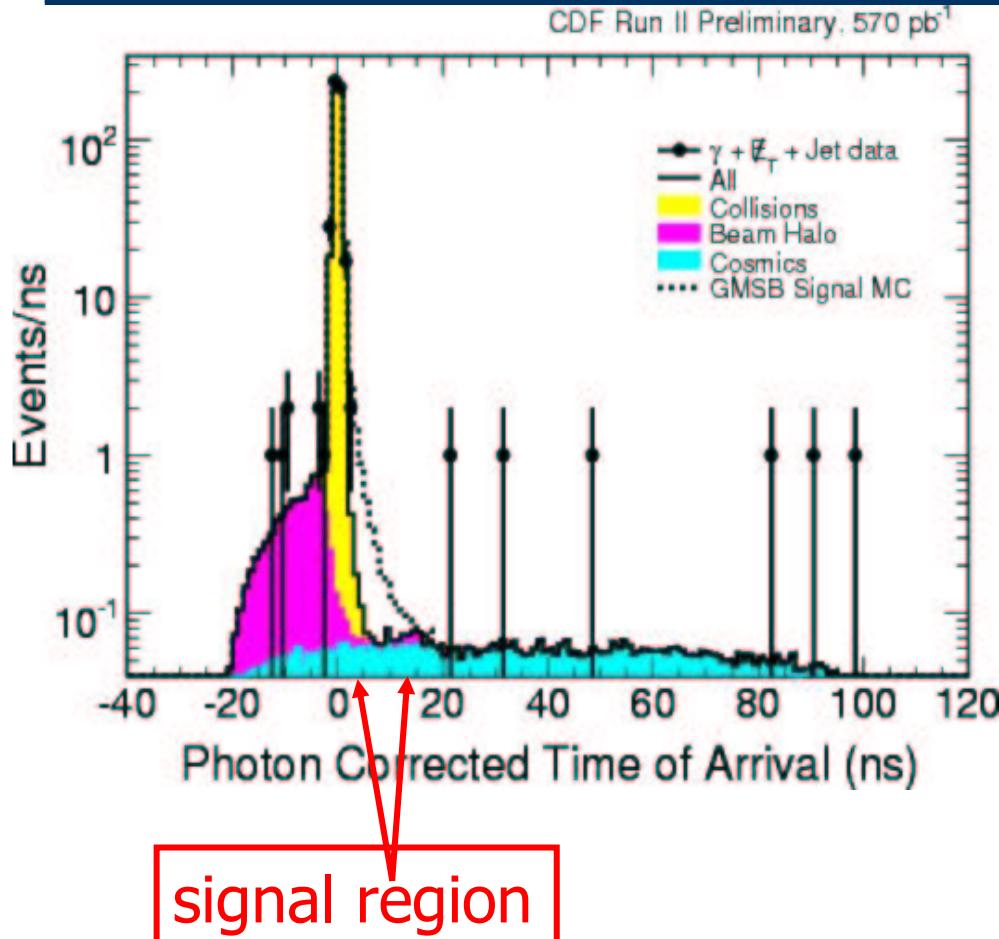
- Relies on EM calorimeter timing detector



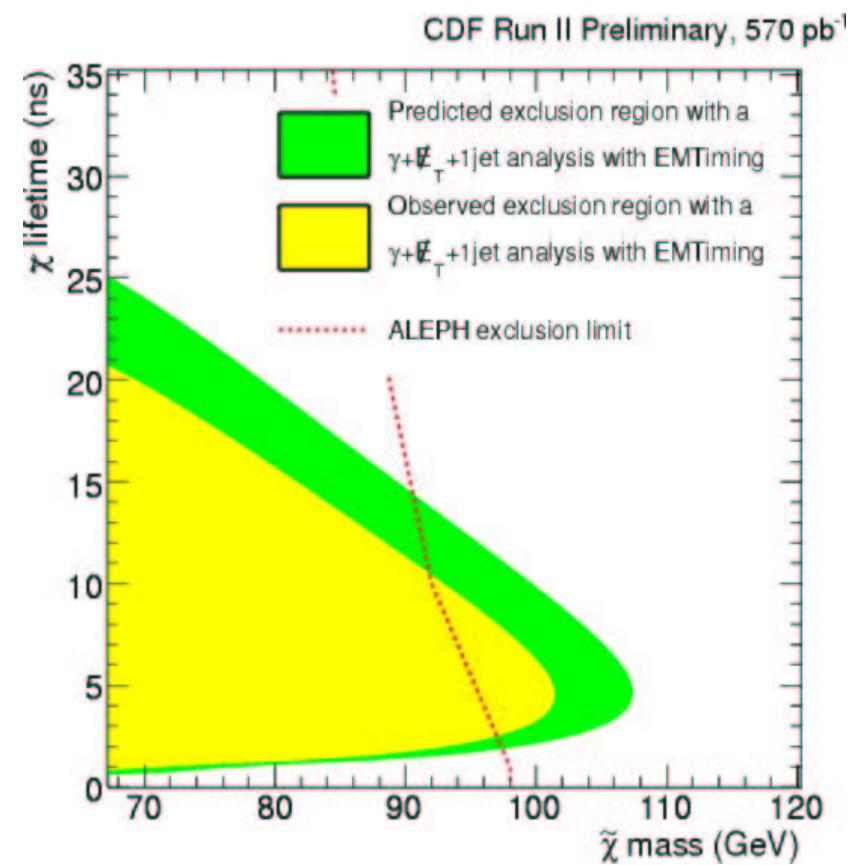
Measure photon arrival time →



Search for Delayed Photons



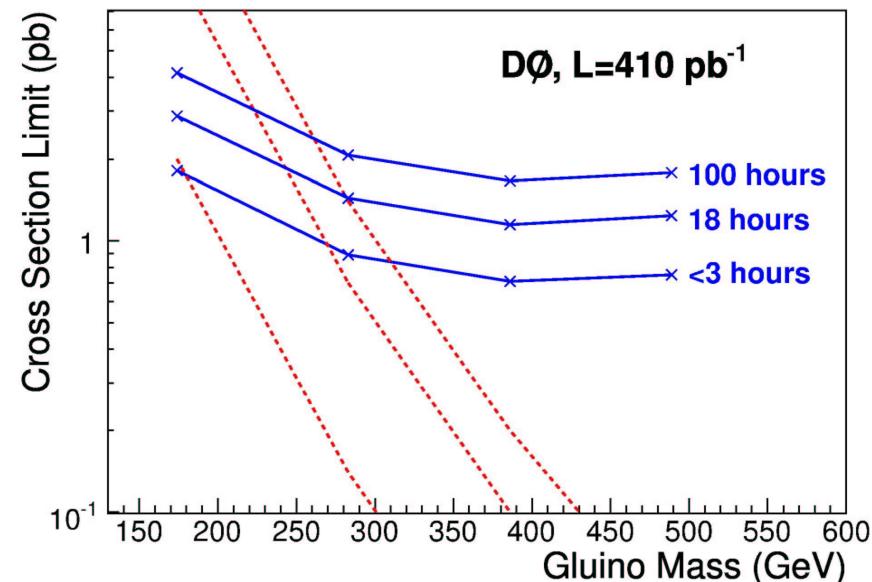
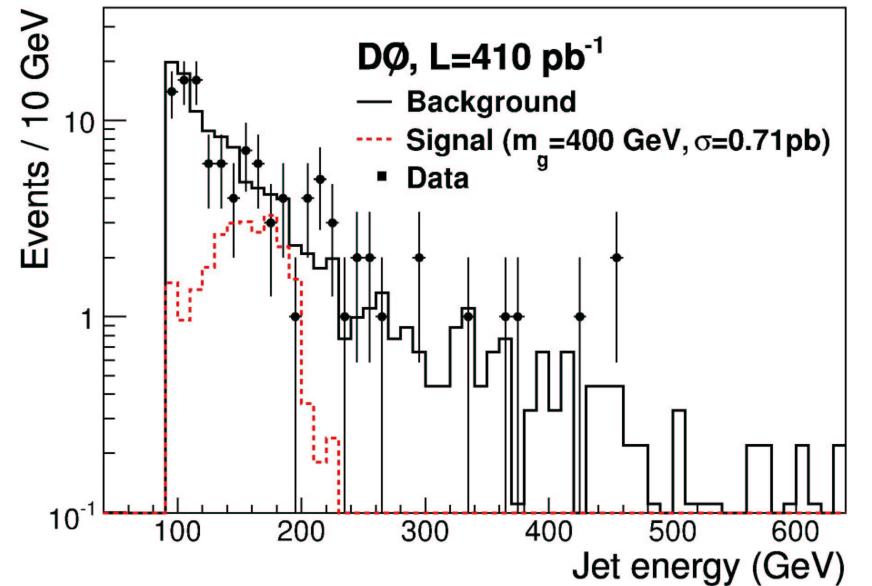
Interpret in GMSB



No evidence for
new physics

D0 Search for Stopped Gluinos

- “Split-SUSY” models (SUSY scalars heavy compared to SUSY fermions) predict long-lived gluinos
 - Stop in calorimeter, decay later (10us – 100 hours)
 - Look for events with calorimeter energy and nothing else

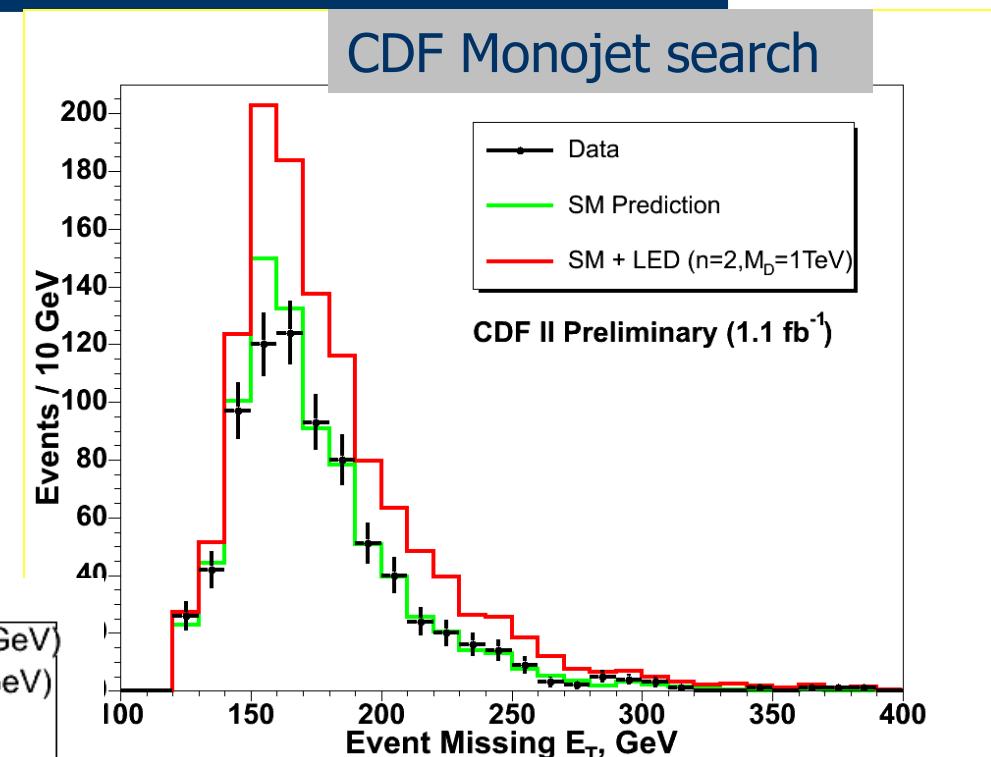
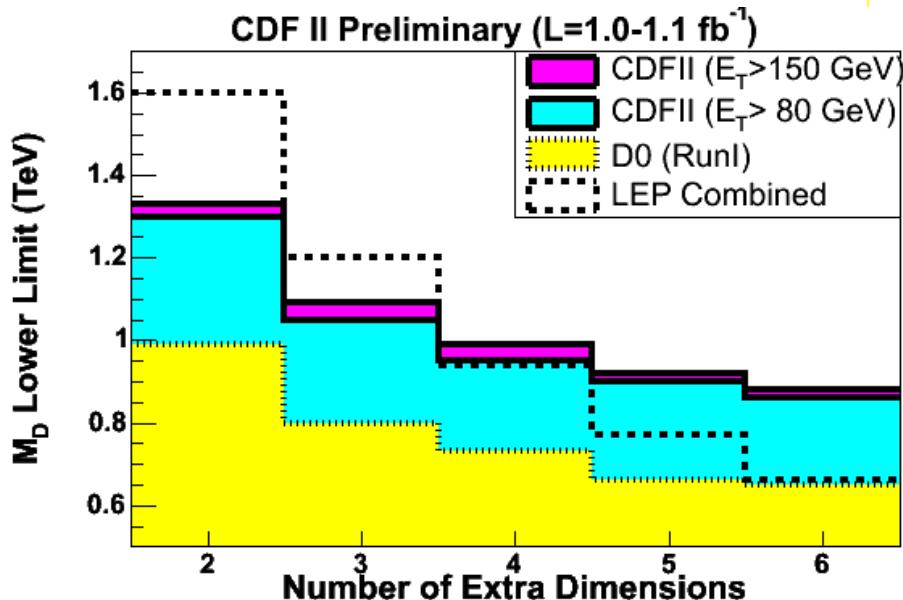


Extra Dimensions

- May be more than four dimensions of space-time
 - “extra” dimensions confined
- Large Extra Dimension models predict ED
 $\sim 10\mu\text{m}$
 - eg, ADD models
 - Experimentally, continuous Kaluza-Klein spectrum
- Small Extra Dimension models
 - eg, Randall-Sundrum
 - Predict towers of KK modes → mass resonances with spacing $O(\text{TeV})$

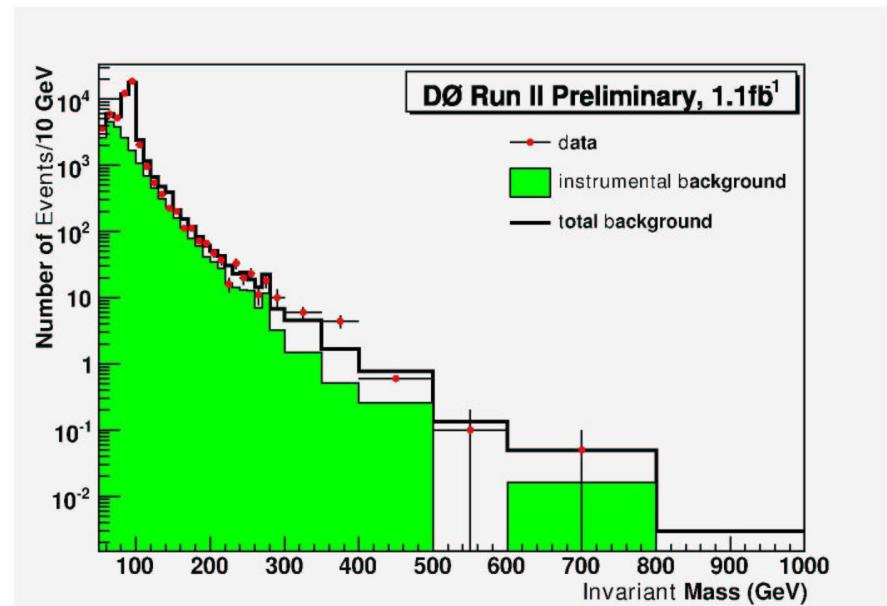
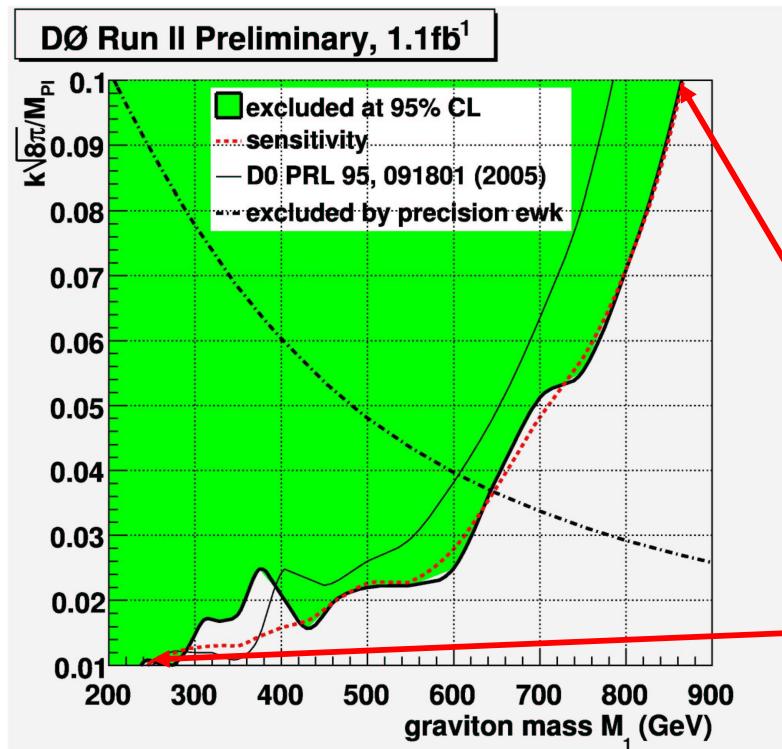
Large Extra Dimensions

- Model independent search for monojet + missing energy, develop range of kinematic selections
- Apply to ADD model



Search for Randall-Sundrum Gravitons

- RS Gravitons spin=2, branching ratio to photons twice that to electrons
- D0 maximizes acceptance, look for EM calorimeter objects w/out track requirement



$M_1 > 865 \text{ GeV}/c^2$

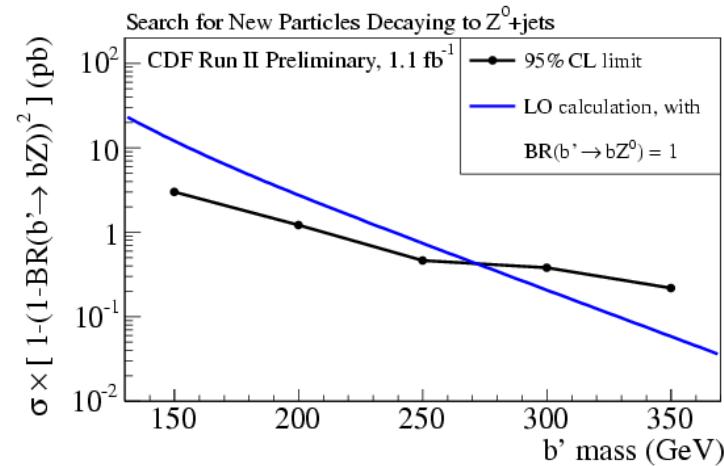
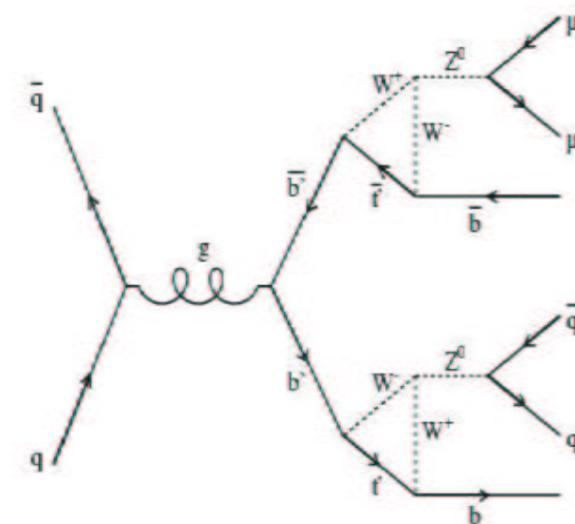
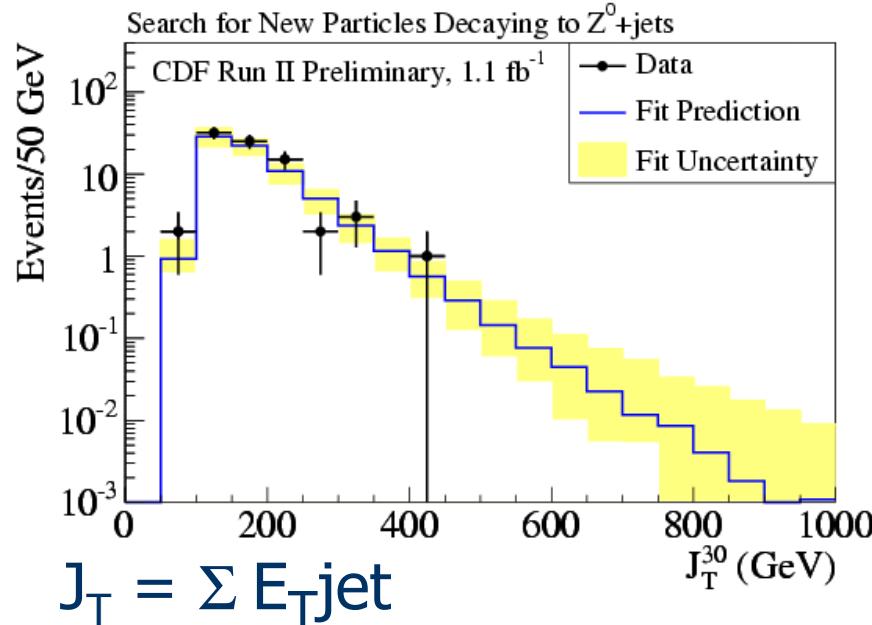
$M_1 > 240 \text{ GeV}/c^2$

Additional New Particles?

- Why are there only three generations? No SM explanation
 - Search for evidence of a fourth generation – t' , b'
- Search for new gauge bosons – Z' , W'
- Search for compositeness – leptons may not be fundamental! → excited electrons and neutrinos
- Is there a connection between leptons and quarks? → leptoquarks

CDF Search for b'

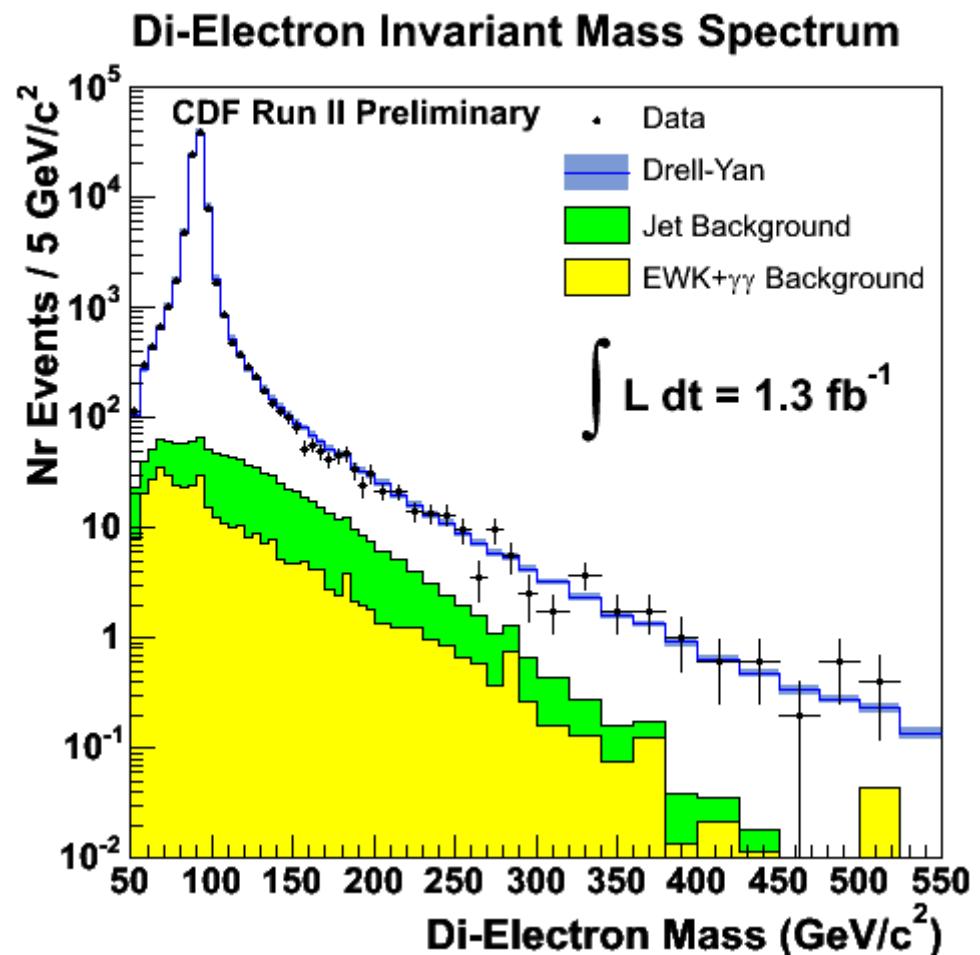
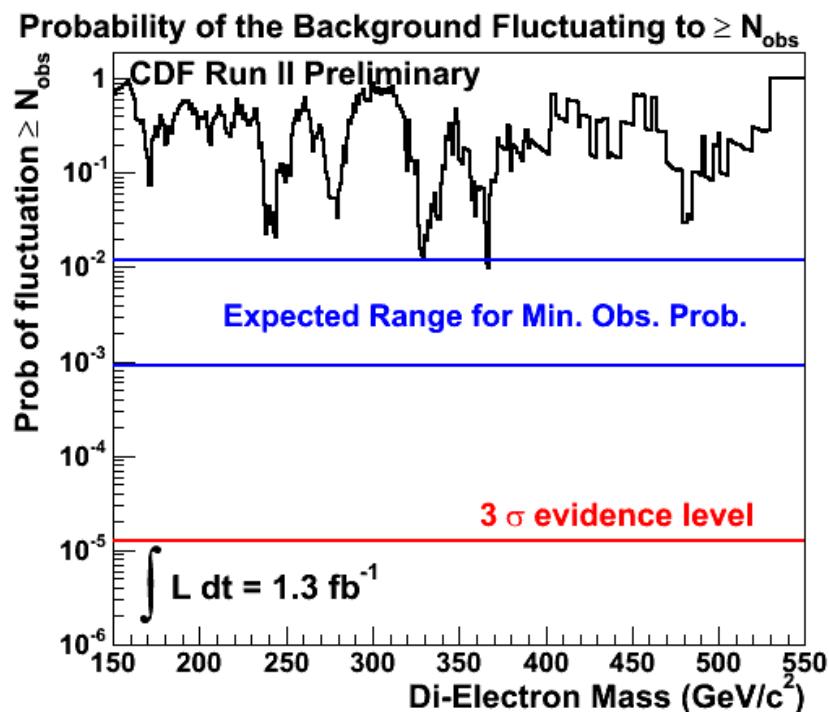
- Signature-based search for particles decaying to $Z+jets$
- Use data ($N_{jet} < 3$) to estimate SM $Z+jets(N_{jet} > 2)$ production
- Apply to b' model



Limit $m_{b'} > 270 \text{ GeV}/c^2$

Searches for Z'

- CDF and D0 have searched for $Z' \rightarrow ee, \mu\mu$
 - Search for high pT, same-flavor leptons, optimize for high-mass Z'
 - Drell-Yan ($\gamma^*/Z \rightarrow ee, \mu\mu$) main SM contribution

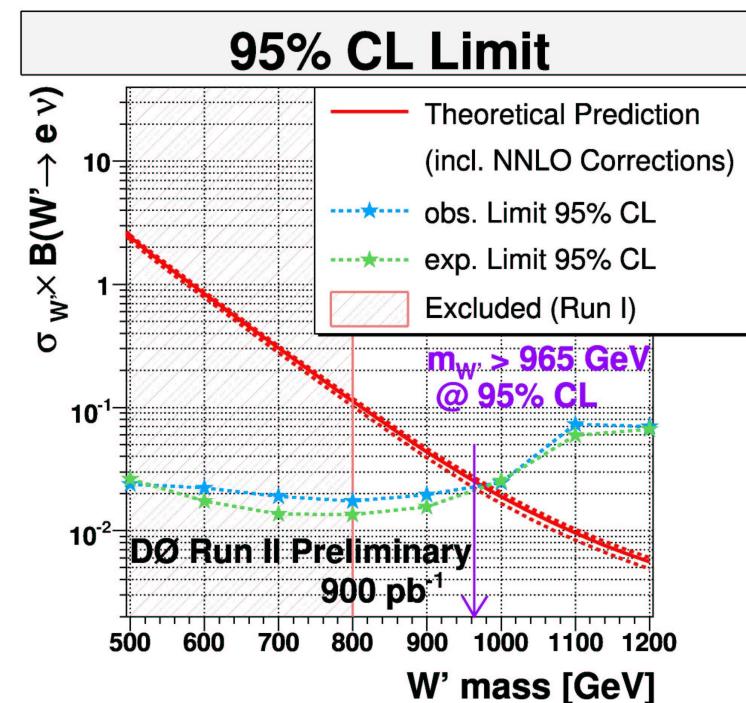
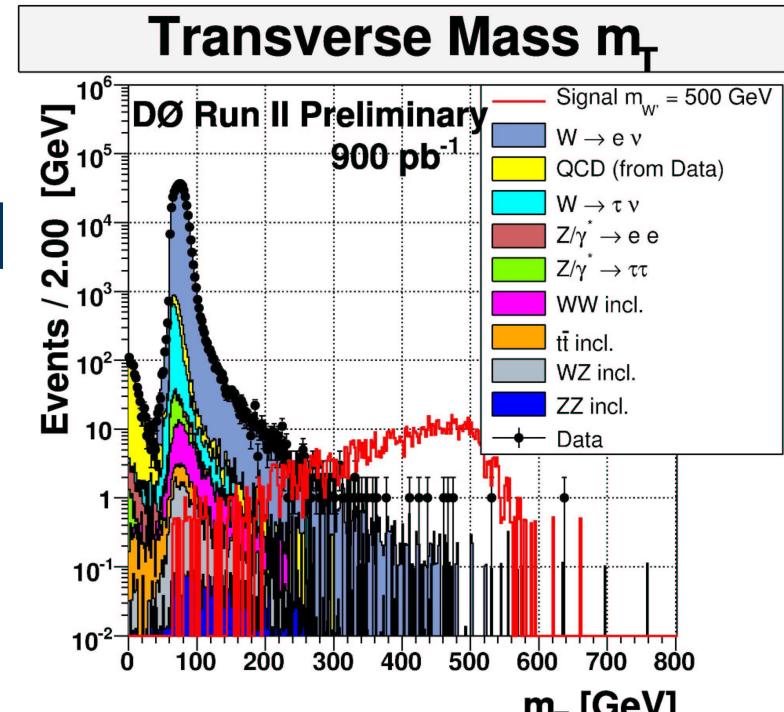


No significant excess observed!

D0's Search for W'

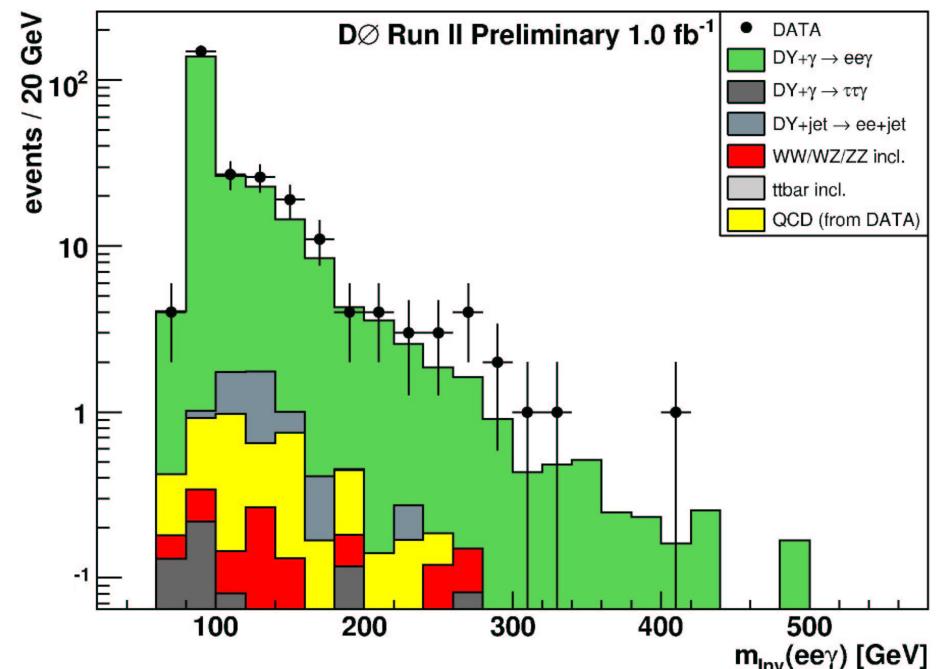
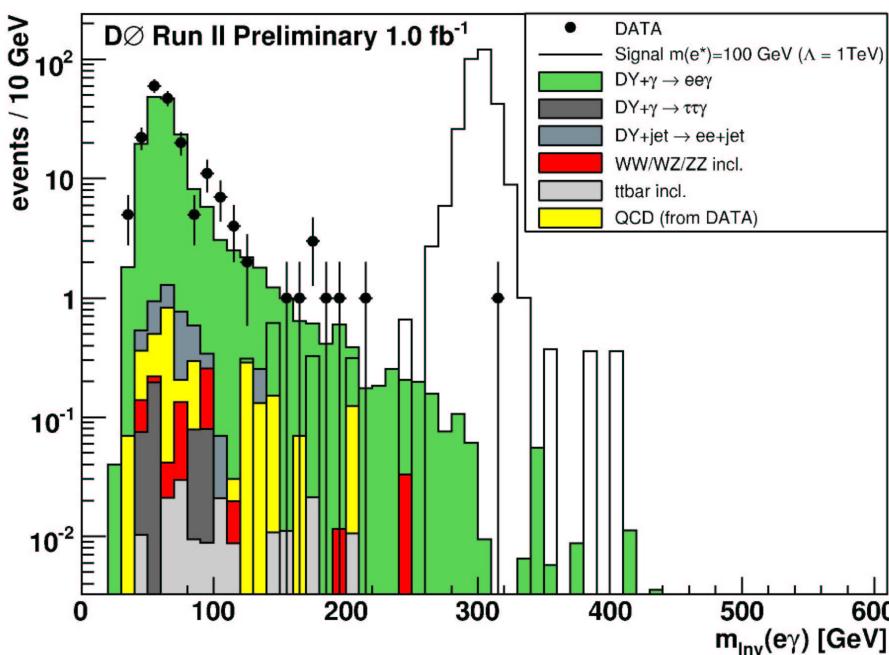
- Search for $W' \rightarrow e\nu$
- use transverse mass distribution
 - $m_T < 30$ for QCD normalization
 - $60 < m_T < 140$ for W normalization
 - $m_T > 150$ for search
- Limit: $W' > 965 \text{ GeV}/c^2$ assuming SM couplings

(See Catalin Ciobanu's talk for CDF's W' analysis)



Excited Leptons at the Tevatron

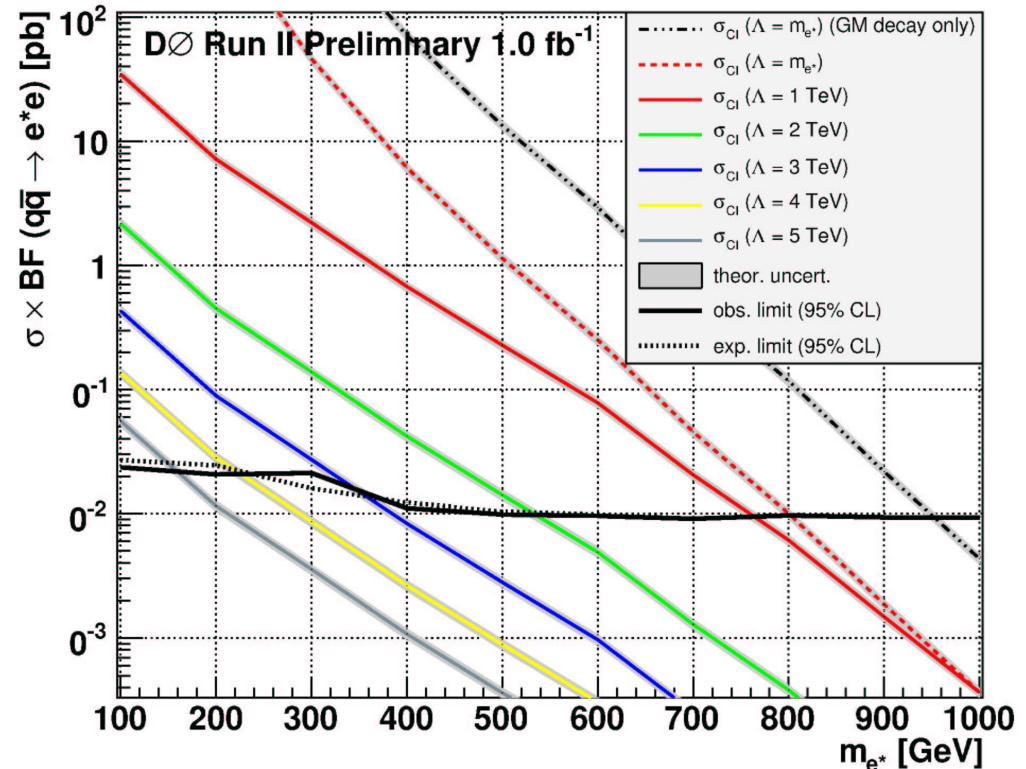
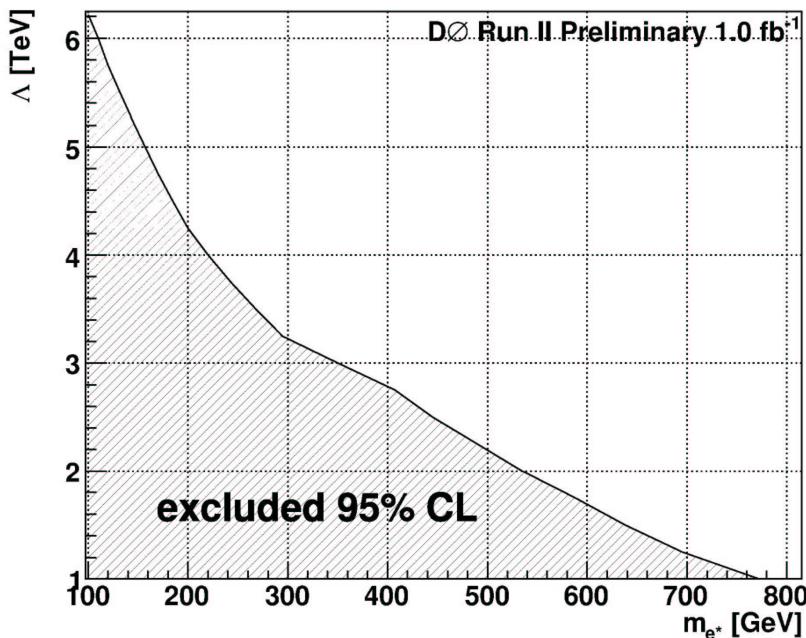
- Possible lepton structure → could observe excited states
- D0's e^* search looks for $ee\gamma$ events from ee^* production, resonance in $ee\gamma$ mass



No evidence for e^* production

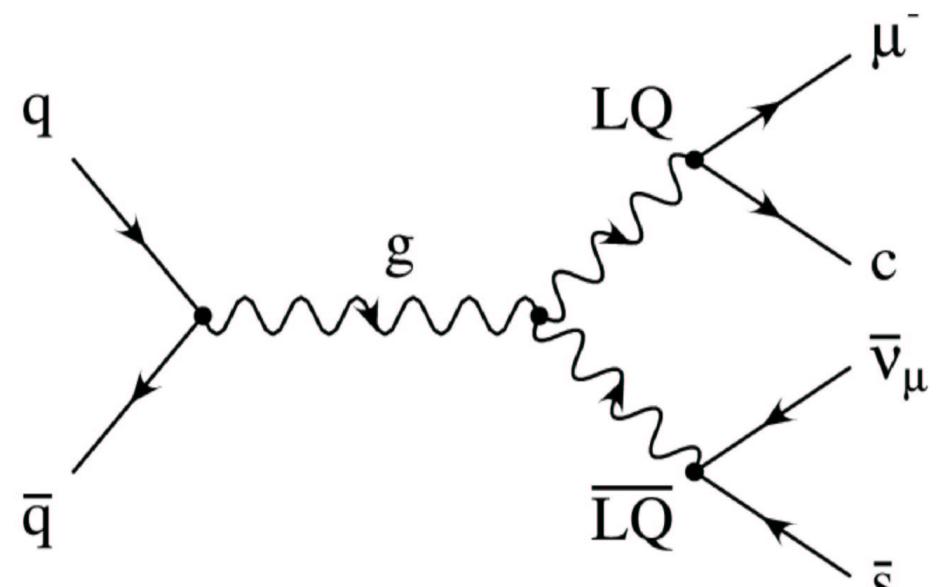
D0 Limits on Excited Electrons

Limits on σ for various values of Λ (compositeness scale)



Leptoquarks

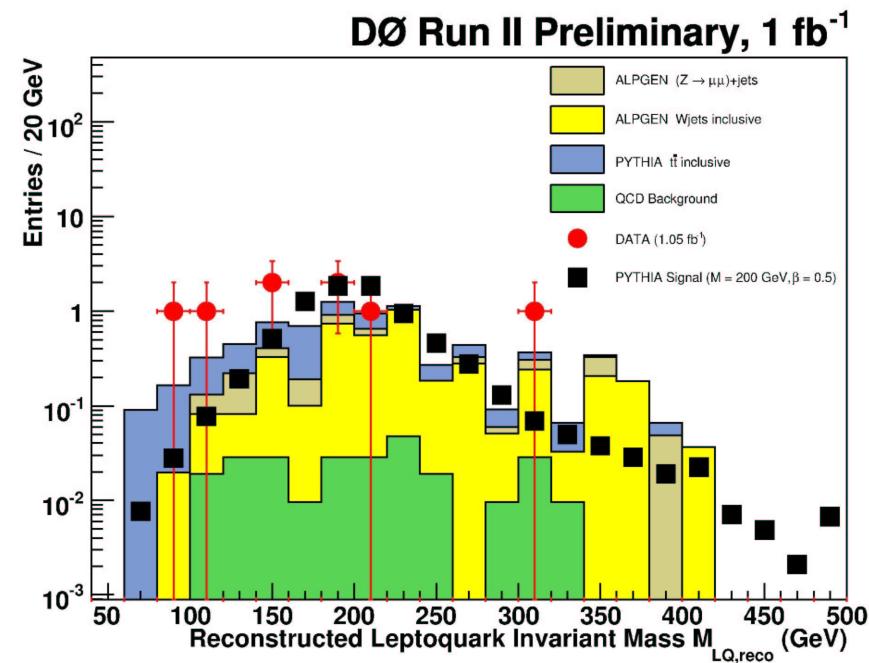
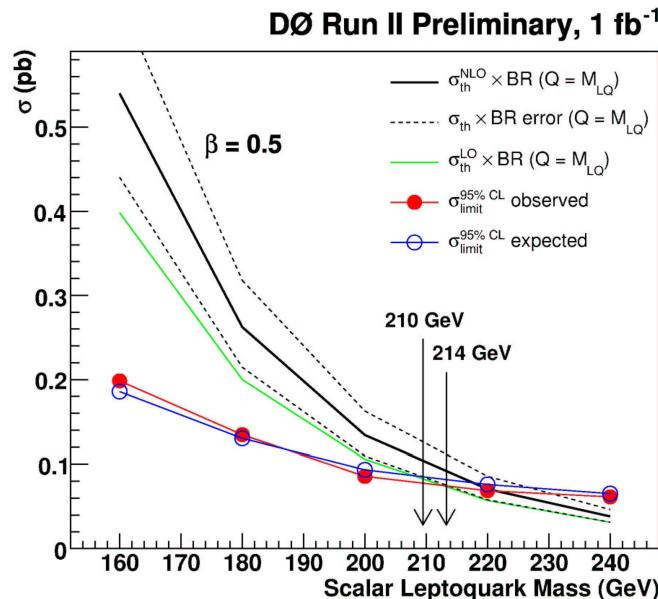
- Leptoquarks (new bosons carrying lepton and baryon numbers) , predicted by many models, searched for at Tevatron and HERA
- Constrained to couple to one family only
 - 1st generation LQ \rightarrow eq
 - 2nd generation LQ \rightarrow μq
 - 3rd generation LQ \rightarrow b $\nu, \tau t$



Tevatron LQ pair production

D0 Leptoquark Search

- 2nd generation – search for energetic muons + jets
 - Reconstruct $M(LQ)$
 - Look for excess at high $M(LQ)$



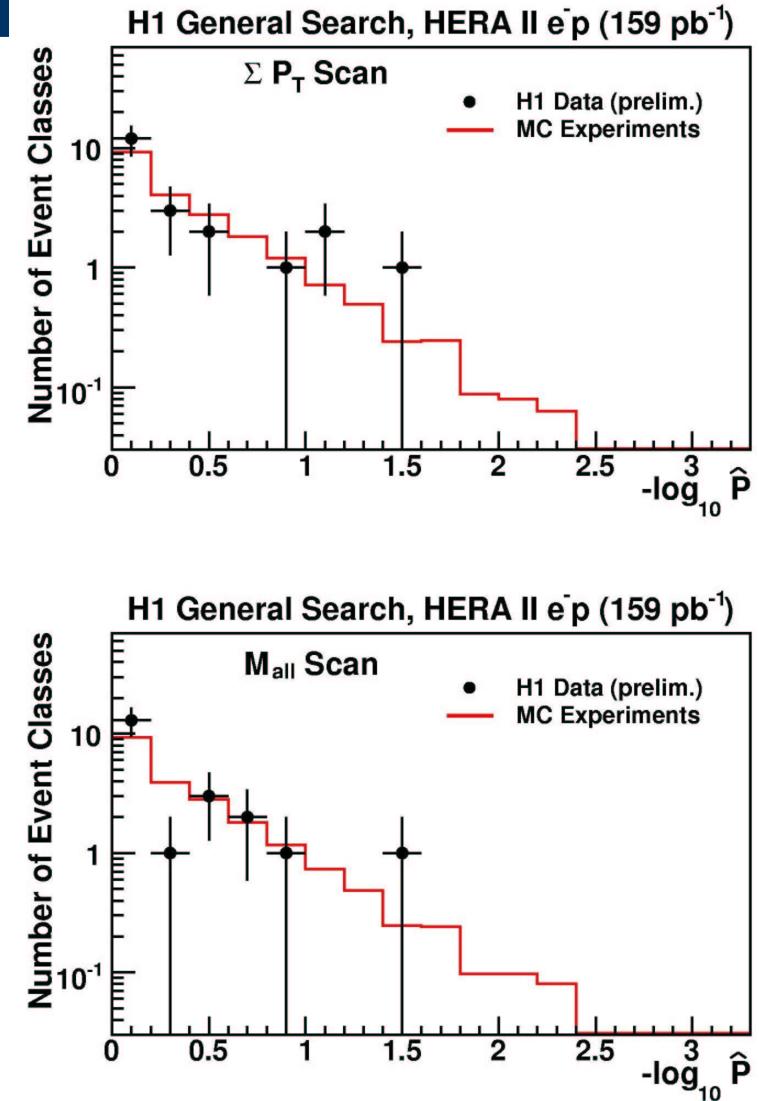
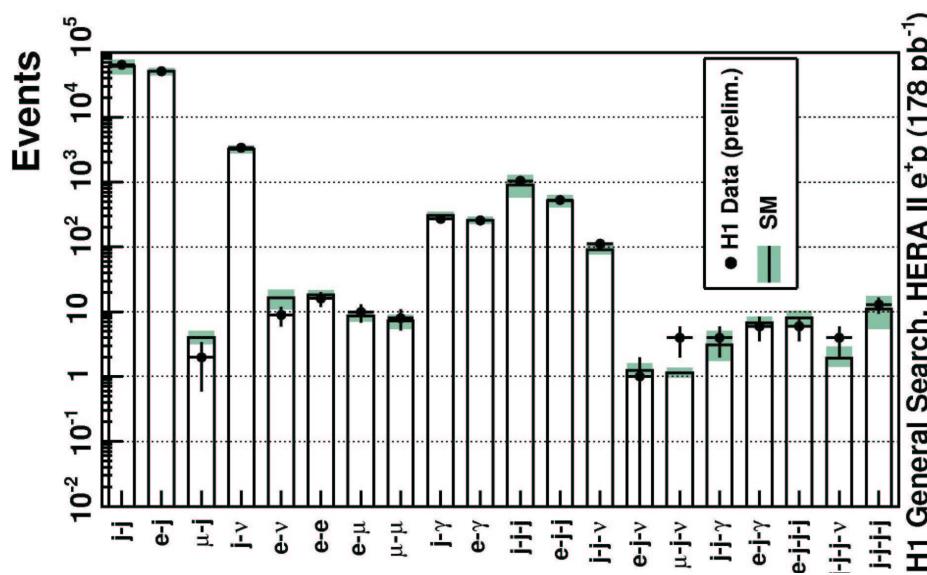
Expect $6.4 \pm 0.7 \pm 0.8$
 Observe 6 (for $M(LQ)=200$)
 → no excess

Signature-based and Global Searches

- Look for anomalies in Standard Model production
 - eg – H1's W observation and excess (see Iris Abt's talk)
 - eg – CDF searches for $\gamma\gamma+X$
- Take a broad look at “everything” (with caveats)
 - Less model dependence for signal
 - But relies on SM modeling for background
 - Not optimized -- sacrifice sensitivity to a specific signal for global sensitivity to the unexpected

Global Search of H1 Data

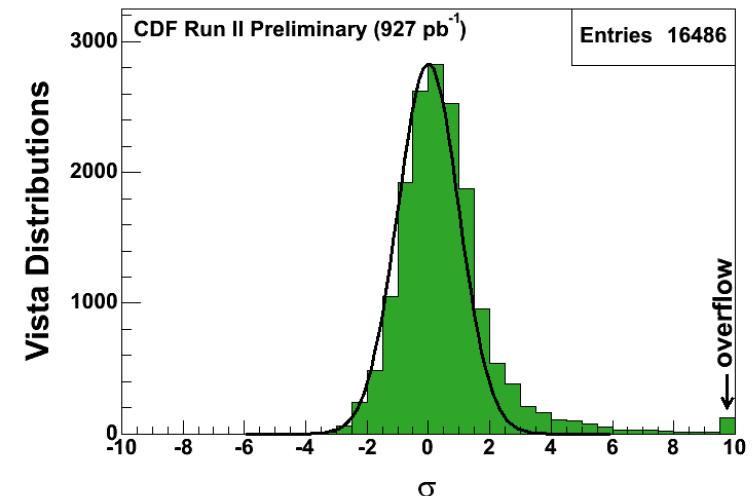
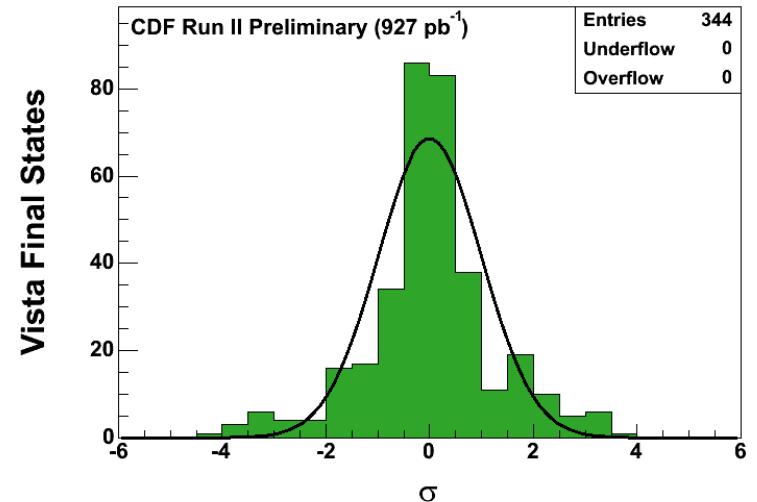
- Search for energetic ($\text{pt} > 20$), isolated particles: $e, \mu, \nu, \gamma, \text{jets}$
- Combinations $\rightarrow 23$ final states
 - Statistical analysis to quantify agreement based on number of events
 - Look for excesses or deficits in M_{all} and Σp_T
 - Find largest deviation, quantify probability, consider number of distributions searched (trials factor)



$5\sigma = 5 - 6 \text{ in } -\log_{10} P$

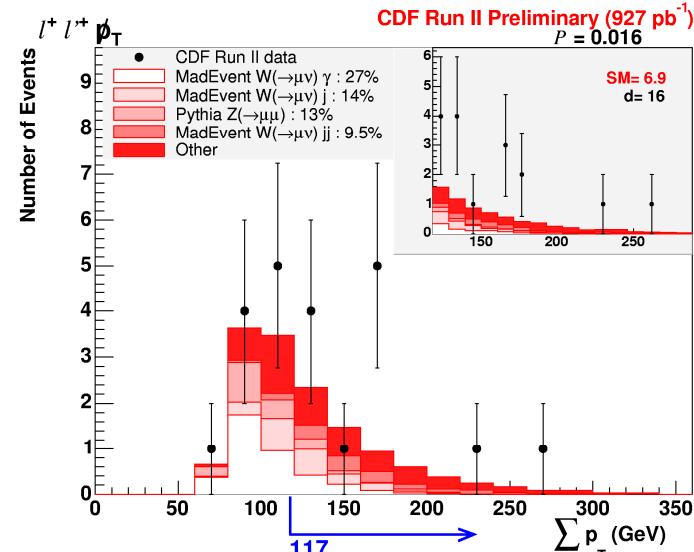
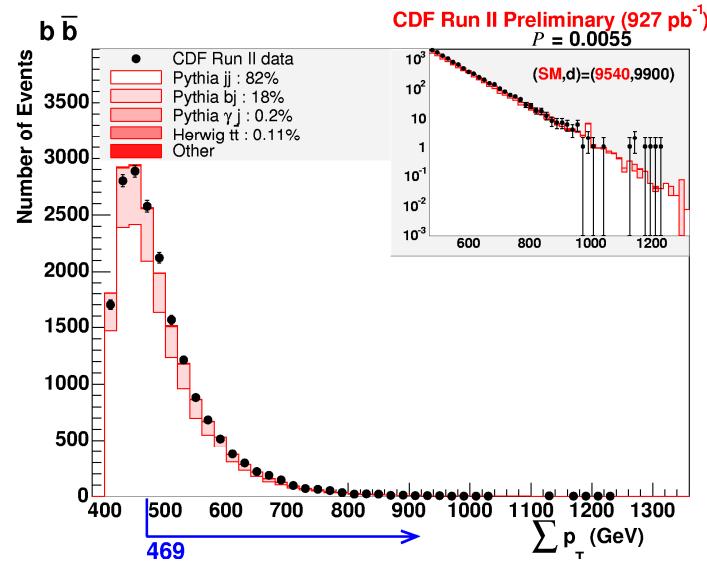
Global Search at CDF -- Vista

- Vista – look at bulk features of high-pT data, in a model-independent way
- Objects: e , μ , τ , γ , jet, b-jet, missing energy
- Combinations of objects into exclusive final states
- Use global comparison to develop correction model for background (take into account known deficiencies in simulation, NLO/LO calc, etc)
- Compare data to background model in 16486 kinematic distributions in 344 final states
 - Take trials factor into account
- Probability of observing largest discrepancy (or larger) = 8%



Global Search at CDF -- Sleuth

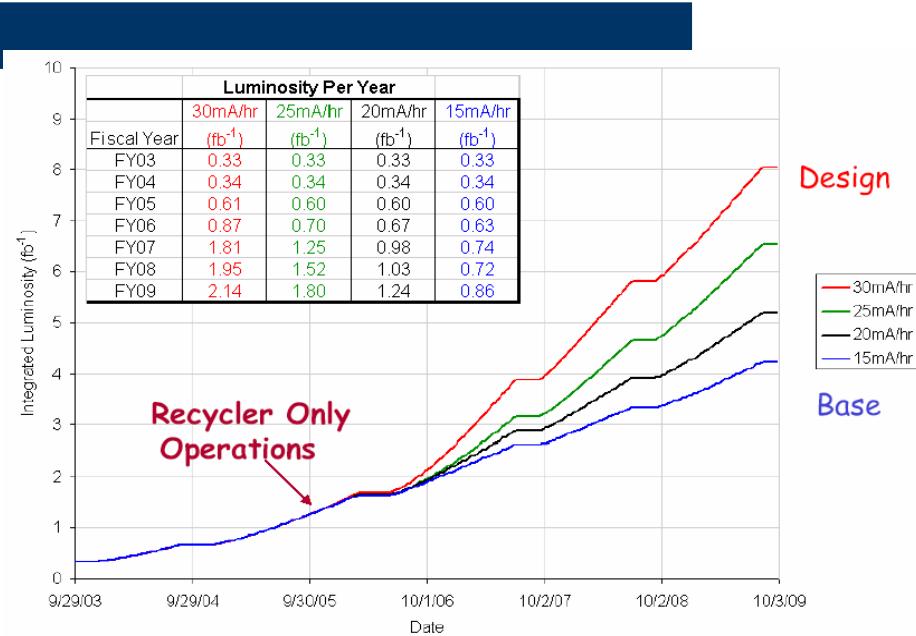
- Sleuth – “quasi-model-independent” search of high Σp_T tails
 - Look for the unexpected!
- Start with Vista final states
 - merge to increase stat significance
- Find most interesting positive deviation from prediction in Σp_T tail
 - Incorporate trials factor
- Interesting analysis, but no significant excess yet
- May be just around the corner...



Sleuth's interesting final states

Conclusions

- Wide variety of signatures, models probed at HERA, Tevatron
 - Many more interesting results to come!
- Hints of New Physics??
 - A few (small) excesses observed, but so far the Standard Model holds
 - General searches – no significant excess yet, but could become significant with more data!
- Can the Tevatron beat the LHC to the next big thing???

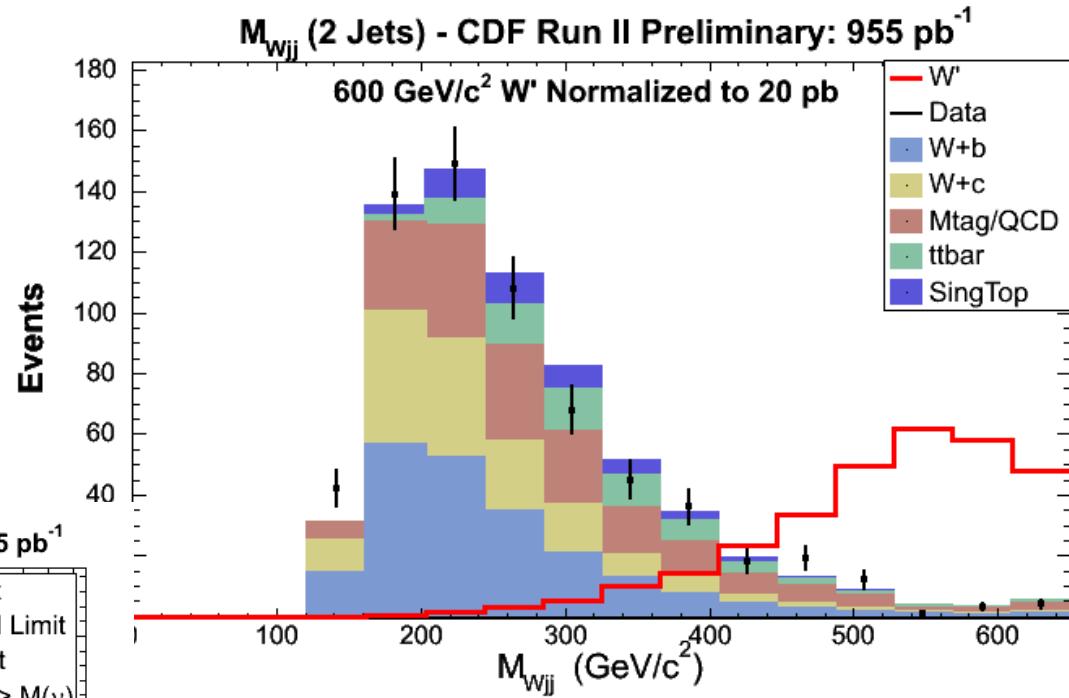
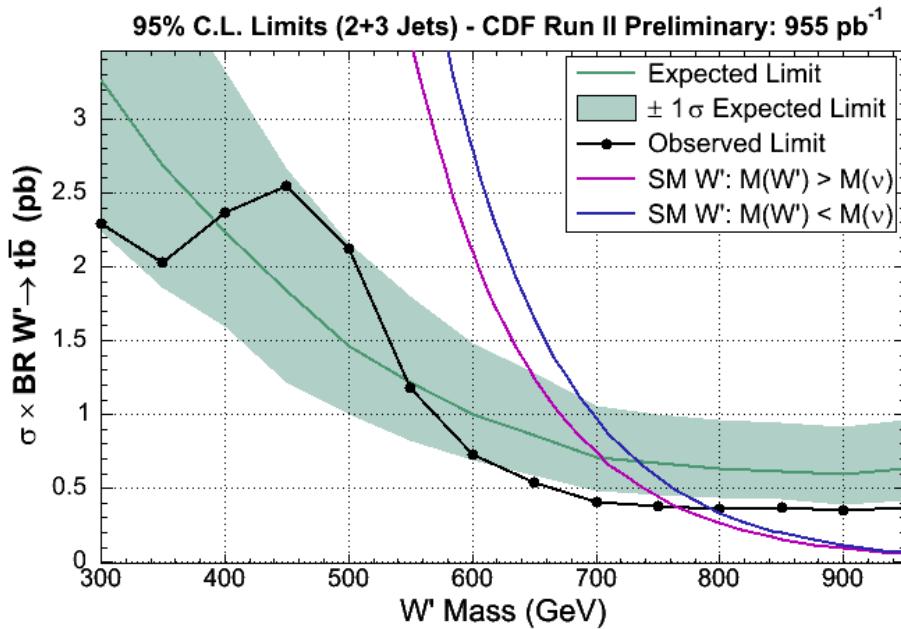


Backup slides



Search for $W' \rightarrow t\bar{b}$ (see Catalin Ciobanu's talk)

- Look for resonance in $M(W'JJ)$ spectrum, using sophisticated tools of single top analysis
- Sensitivity to W' between 300 and 950 GeV/c^2

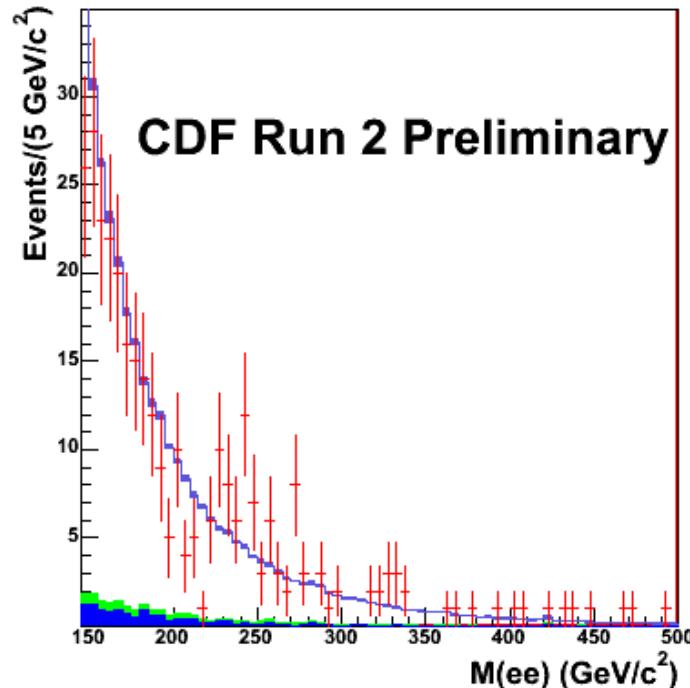
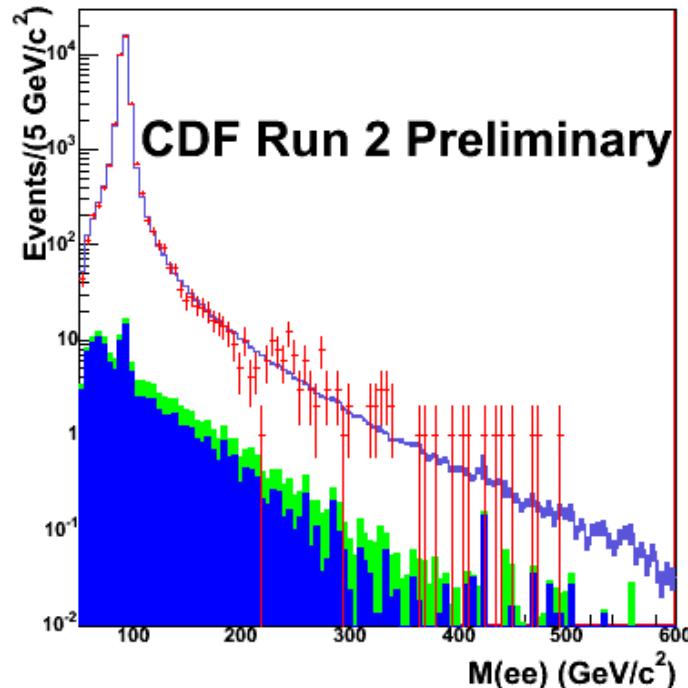


No excess seen:
 $MW' > 760 \text{ GeV}/c^2$ ($MW' > M_{\nu R}$)
 $MW' > 790 \text{ GeV}/c^2$ ($MW' < M_{\nu R}$)

CDF Z' Search (II)

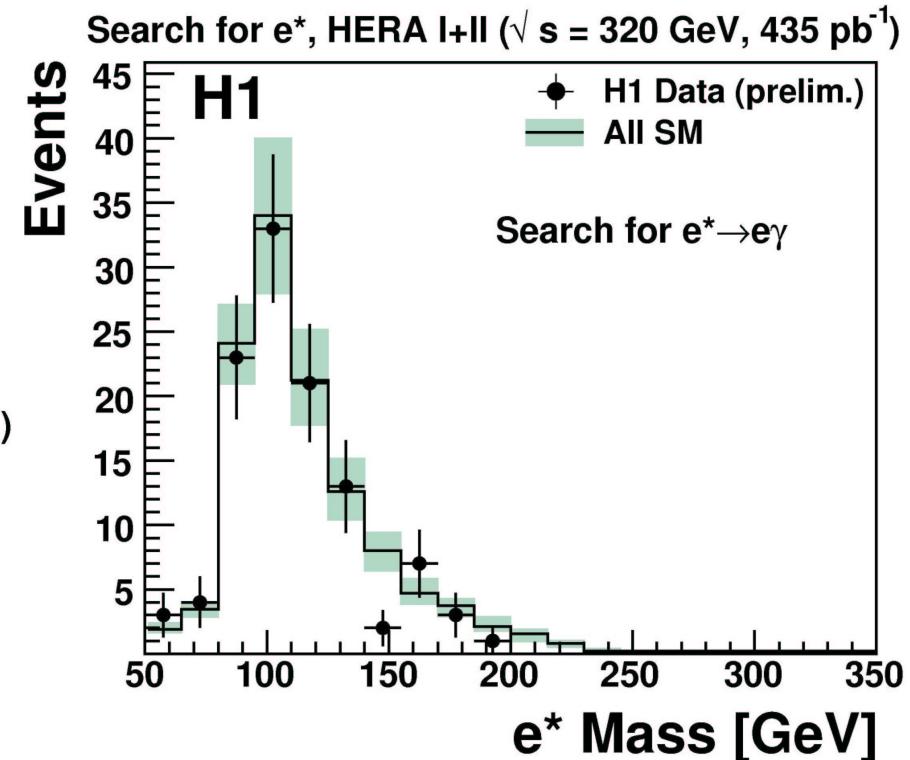
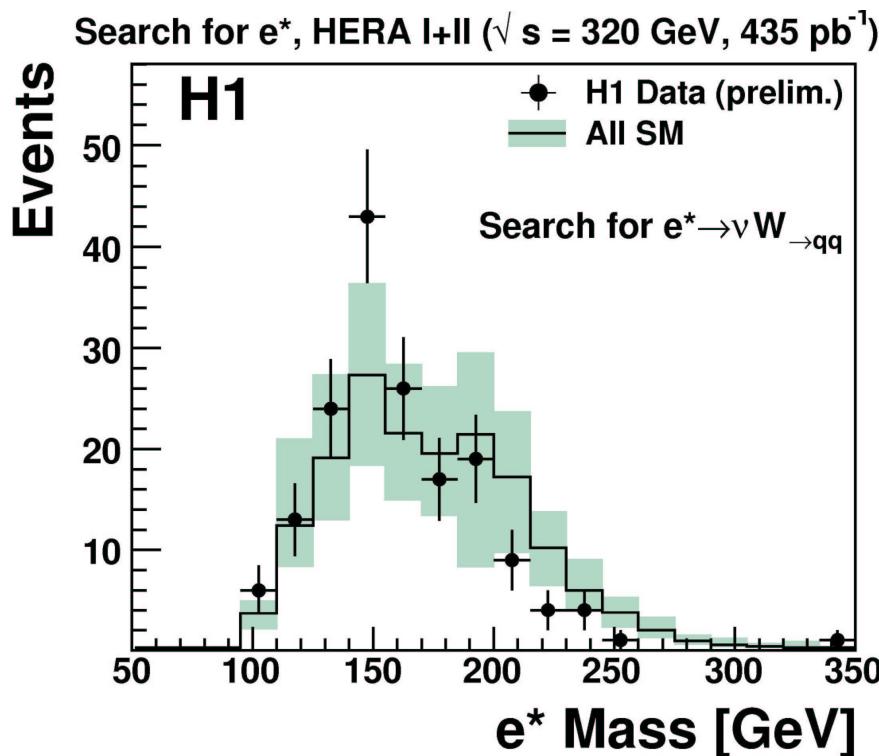
- CDF result from another Z' search
 - Focus on a specific region – 200 – 250 GeV/c²
 - Small excess seen at 240 GeV/c² ($2.8 - 3.7 \sigma$, depending on details of calc)
 - Probability to observe this level of excess or higher from SM only is 1.7%
 - Plan: freeze cuts and look at next set of data
 - Stay tuned !

0.9 fb⁻¹



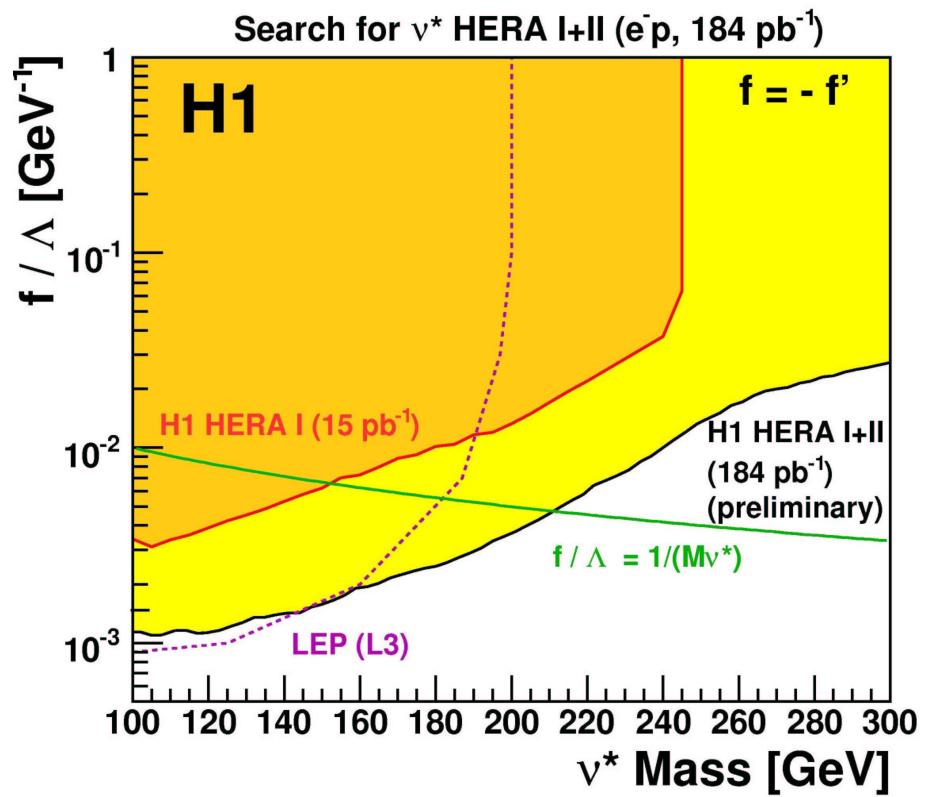
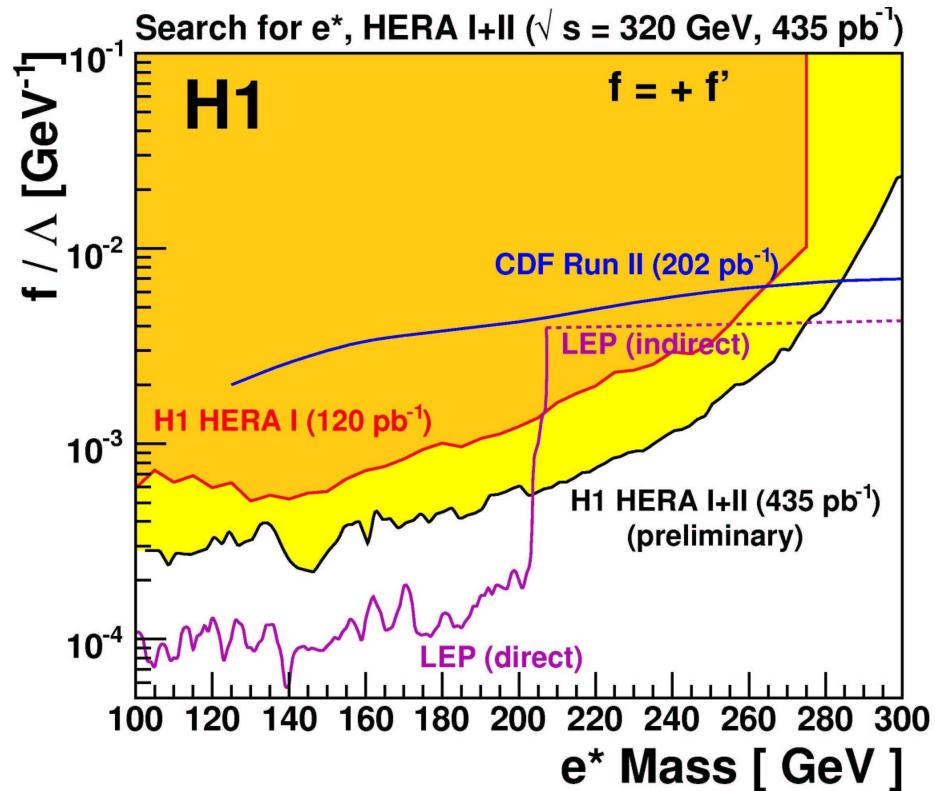
HERA excited lepton search

- H1 analyses for e^* and ν^* with full dataset



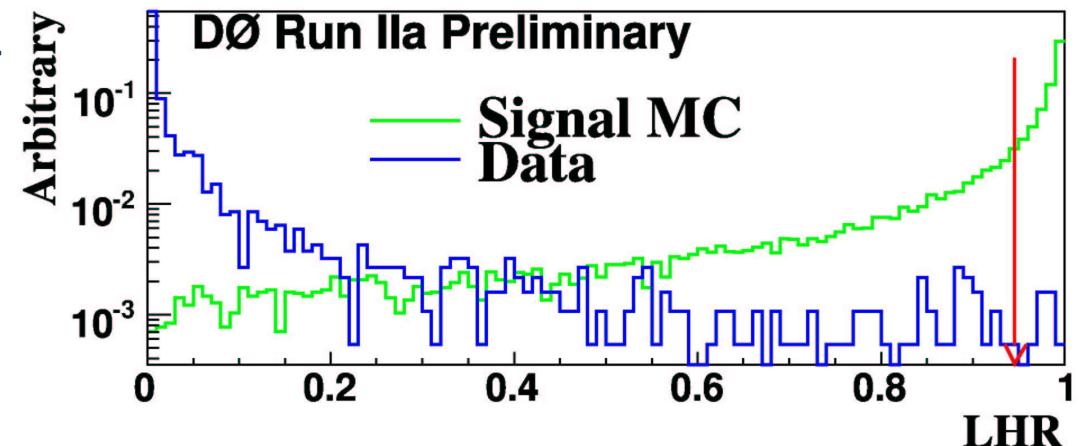
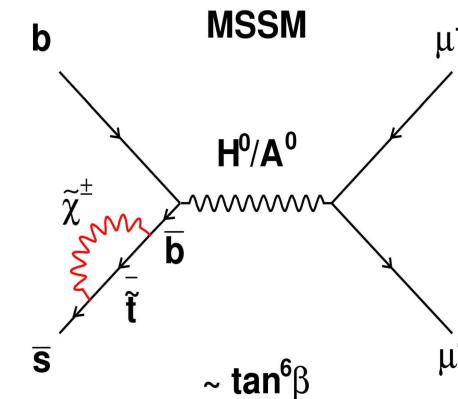
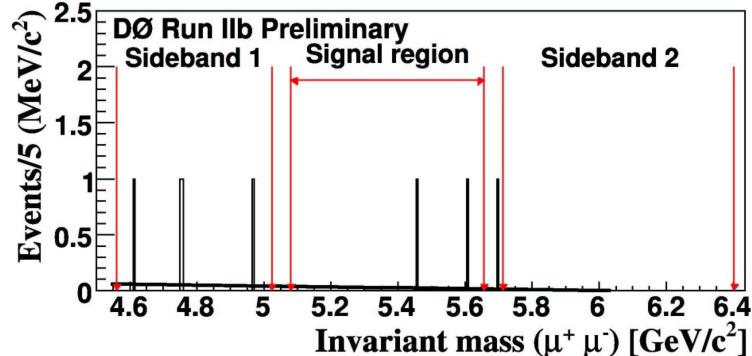
- Single production, search for resonance:
 $\nu^* \rightarrow \nu g, eW, \nu Z$
 $e^* \rightarrow e\gamma, \nu W, eZ$

H1 excited leptons limits



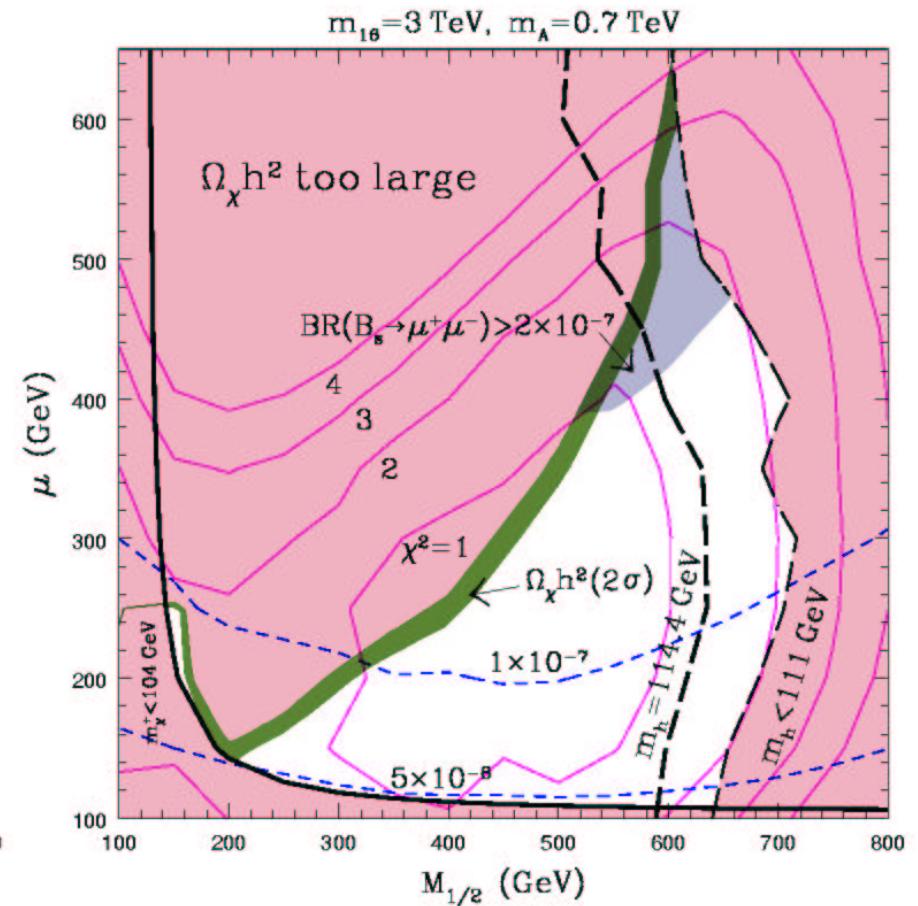
Indirect SUSY searches -- $B_s \rightarrow \mu^+ \mu^-$

- Standard model predicts $B_s \rightarrow \mu^+ \mu^- = (3.8 \pm 0.9) \times 10^{-9}$
- SUSY rate may be enhanced $\sim \tan^6 \beta$
- Separate from huge background using likelihood ratio w/event characteristics, eg:
 - decay length significance
 - B-meson isolation
 - Pointing angle
 - B and muon impact parameter
 - Vertex information



$B_s \rightarrow \mu\mu$: Result and Future

- Result – observation consistent with background expectation
- Branching Ratio Limits:
 - CDF (780 pb⁻¹):
 - $\text{BR}(B_s \rightarrow \mu\mu) < 10 \times 10^{-8}$ at 95% C.L.
 - DØ (2 fb⁻¹):
 - $\text{BR}(B_s \rightarrow \mu\mu) < 9.3 \times 10^{-8}$ at 95% C.L.
- Future: Tevatron will probe values of 2×10^{-8}



Searches for Stop/Sbottom

- Third generation squarks could be light!
- Devise specific searches
 - Production : stop or sbottom pairs, or through gluino decays
 - Decay:
 - $b \rightarrow b\chi^0$
 - Stop depends on mass:
 - Heavy: $t \rightarrow t\chi^0$
 - Medium: $t \rightarrow b\chi^\pm \rightarrow bW\chi^0$
 - Light: $t \rightarrow c\chi^0$

Search for $t \rightarrow c\chi^0$ -- acoplanar charm jets + Missing ET

